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EPA Technical Study on the Safety of Emission Controls for Nonroad Spark-Ignition Engines < 50 Horsepower

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Executive Summary

The purpose of this technical study is to assess the incremental impact on safety of applying the advanced emission control technology expected to meet the new emission standards under consideration for particular subcategories of nonroad engines and equipment, focusing on the risk of fire and burn to consumers in use. The study will be part of the rulemaking record for the proposed standards and satisfies the provisions of section 205 of PL 109-54, which requires the Environmental Protection Agency (EPA) to assess potential safety issues, including the risk of fire and burn to consumers in use, associated with the proposed emission standards for nonroad spark-ignition (SI) engines under 50 horsepower (hp). As is discussed below, this technical study concludes that new emission standards would not increase the risk of fire and burn to consumers in use. In fact, in a number of circumstances the study demonstrates a directional decrease in risk.

This study evaluates new exhaust and evaporative emission standards for nonhandheld (NHH) and handheld (HH) equipment in the Small SI engine category and outboard (OB) and personal watercraft (PWC) engines and vessels in its Marine SI engine category. The new emission standards addressed by this study include:

- New catalyst-based hydrocarbon plus oxides of nitrogen (HC+NOx) exhaust emission standards for NHH engines;
- New HC+NOx and carbon monoxide (CO) exhaust emission standards for OB/PWC engines and vessels;
- New fuel evaporative emission standards for NHH and HH equipment; and
- New evaporative emission standards for OB/PWC engines and vessels.

The following summarizes EPA's assessment of the incremental impact on safety of new standards in each of these four areas. For each new standard, EPA concludes that the forthcoming Phase 3 emission standards may be implemented without any incremental increase in risk of fire or burn to consumers in use. Furthermore, the testing and analysis also indicates that compliance with the Phase 3 emissions standards will most likely reduce the risk to consumers of operating Phase 2 products in these subcategories.

Exhaust emission standards for NHH engines: We conducted the technical study of the incremental risk of catalyst-based HC+NOx emission standards for NHH engines on several fronts. First, working with the Consumer Product Safety Commission (CPSC), EPA evaluated CPSC reports and databases and other outside sources to identify those in-use situations which create fire and burn risk for consumers. Six basic scenarios were identified for evaluation. Second, EPA conducted extensive laboratory and field testing of both current technology (Phase 2) and prototype catalyst-equipped advanced technology engines and equipment (Phase 3) to assess the emissions performance and thermal characteristics of the engines and equipment. EPA also contracted with Southwest Research Institute (SwRI) to conduct design and process Failure Mode and Effects Analyses (FMEA) comparing Phase 2 and Phase 3 compliant engines and equipment to evaluate incremental changes in risk probability as a way of evaluating the incremental risk of going from Phase 2 to Phase 3 emission standards. Our technical work and subsequent analysis of all of the data and information strongly indicate that catalyst-based standards can be implemented without an incremental increase in the risk of fire or burn to the consumer. In many cases, the designs used for catalyst-based technology can lead to an incremental decrease in such risk.

Evaporative emission standards for NHH and HH engines and equipment: EPA also evaluated the incremental risk of fire and burn to consumers for the evaporative emission standards we are considering for NHH and HH equipment. For both subcategories we are considering fuel tank and fuel hose permeation standards similar to those in place for other nonroad SI engines and vehicles, such as all-terrain vehicles and off-highway motorcycles. In addition, for NHH equipment we are considering running loss controls designed to reduce emissions related to fuel in the tank evaporating to the atmosphere during equipment operation. Working with CPSC, EPA evaluated CPSC databases to identify those in-use situations which create fire and burn risk for consumers. Fuel leaks from tanks or fuel hoses on HH and NHH equipment were identified as the major safety concern for evaluation.

Fuel tanks used on HH and NHH equipment are constructed of different types of materials using different processes and each has a potentially different approach to controlling tank permeation emissions. EPA evaluated both current and treated fuel tanks in the laboratory for several years and identified no incremental safety risk related to the technologies for reducing permeation emissions. Most fuel hoses meet American Society for Testing and Materials (ASTM) and Society of Automotive Engineers (SAE) standards, and the types of fuel hoses needed to reduce permeation are in widespread use today. In fact, some lawn and garden equipment already uses low permeation hose.

Beyond this, in situations where custom fuel hoses are used there are the ASTM and manufacturer specific test procedures and requirements that assure proper in-use performance. With regard to fuel tanks, there are manufacturer specific test procedures and requirements which manufacturers apply to current products and will continue to use in the future. The emissions durability portion of EPA's permeation test procedures inherently includes the types of evaluations needed to identify the potential for leaks in-use. The FMEA conducted by SwRI also looked at systems interaction between engine modifications and the fuel system and determined that permeation controls and running loss controls on NHH fuel tanks would not increase the fire and burn risk probability but could in fact lead to directionally better systems from a safety perspective. Overall, there is no incremental safety risk in applying advanced technology to reduced evaporative emissions from HH and NHH engines and equipment, and to some degree the use of technology can lead to an incremental decrease in risk.

Exhaust emission standards for OB/PWC engines and vessels: EPA is also considering new HC+NOx and CO exhaust emission standards for OB/PWC engines and vessels. The US Coast Guard (USCG) keeps a close watch over marine safety issues, and USCG, as well as several other organizations, including SAE, Underwriters Laboratories (UL), and the American Boat and Yacht Council (ABYC), already have safety standards which apply to engines and fuel systems used in these vessels. The four-stroke and two-stroke direct injection engine technologies that are likely to be used to meet the exhaust emission standards being considered by EPA for OB/PWC are in widespread use in the vessel fleet today. These more sophisticated engine technologies are replacing two-stroke carbureted engines. These four-stroke and two-stroke direct injection engines meet applicable USCG and ABYC safety standards and future products will do so as well. The proposed emission standards must be complementary to the already existing safety standards and our analysis indicates that this is the case. There are no known safety issues with this technology compared to the two-stroke carbureted engines and arguably the newer technology engines provide safety benefits due to improved engine reliability in use. Based on the applicability of USCG and ABYC safety standards and the good in-use experience with advanced technology engines in the current vessel fleet, EPA believes new emission standards would not create an incremental increase in the risk of fire or burn to the consumer.

Evaporative emission standards for OB/PWC engines and vessels: EPA also analyzed the incremental impact on safety for the fuel hose and fuel tank permeation and fuel tank diurnal evaporative emission standards it is considering for marine vessels. As with the exhaust emission standards, the proposed emission standards must complement existing USCG, ABYC, and SAE test procedures and safety standards related to fuel hoses for marine vessels and USCG, UL, and ABYC standards and test procedures covering portable and installed fuel tanks. All of these standards are designed to address the in-use performance of fuel systems with the goal of eliminating fuel leaks. The low permeation fuel hoses needed to meet the Phase 3 requirements would need to pass these standards, and evidence indicates that this would occur. In fact, fuel hoses meeting these requirements are available today. The low permeation fuel tanks needed to meet the Phase 3 requirements would also need to pass the applicable USCG, UL, and ABYC standards; work conducted by EPA and vendors supplying the marine tank industry indicates that the technology needed to meet these standards can be applied without an incremental increase in risk over current systems.

EPA is also considering fuel tank diurnal emissions standards for fuel tanks used on Marine SI engines and vessels. For PWC and portable OB fuel tanks, this would likely entail the use of venting control technology already commonly used in these tanks. For vessels with installed fuel tanks this would likely employ the use of activated carbon canisters to capture this vapor. Such canisters have been used safely on automobiles for more than 30 years and a prototype fleet run last summer revealed no safety concerns. Overall, there should be no incremental increase in risk of fire or burn to consumers in applying advanced technology to reduce evaporative emissions from

OB/PWC engines and vessels. In fact, the reduction of permeation emissions is likely to incrementally decrease safety risks from fire in the under floor areas on boats where the tanks and hoses are installed.

In summary, EPA has evaluated the incremental impact on safety focusing on the risk of fire and burn to consumers associated with the advanced technologies expected to meet the new emission standards EPA is considering for the Small SI engine and Marine SI engine categories under 50 hp. Laboratory and field testing, the FMEA analyses,, the mandatory and consensus test procedures and standards which apply to these engines and fuel systems, and the availability of certain components and engines which already meet the Phase 3 standards lead EPA to conclude that new emission standards would not cause an incremental increase in risk of fire or burn to consumers in use. Instead, compliance with the new standards should reduce certain safety concerns presented by current technologies.

TABLE OF CONTENTS

List of Acronyms

ABYC	American Boating and Yacht Council
ANSI	American National Standards Institute
ASAE	American Society of Agricultural Engineers
ASTM	American Society for Testing and Materials
BP	Barometric Pressure
°C	Degrees Celsius
CAA	Clean Air Act
CAD	Crank Angle Degrees
CARB	California Air Resources Board
Class I	Nonhandheld Engines <225cc
Class II	Nonhandheld Engines >225cc and less than 19kW
CO	Carbon monoxide
CFR	Code of Federal Regulations
CPSC	Consumer Product Safety Commission
cpsi	Cells per square inch
CVS	Constant Volume Sampler
E85	mixture of 85% ethanol and 15% gasoline
ECU	Engine Control Unit
EFI	Electronic Fuel Injection
EPA	Environmental Protection Agency
ETC	Electronic Throttle Control
EVOH	Ethyl Vinyl Alcohol
°F	Degrees Fahrenheit
FMEA	Failure Modes and Effects Analysis
FR	Federal Register
g/kW-hr	Grams per kilowatt hour
HC	Hydrocarbons
HDPE	High-Density Polyethylene
NHH	Non-handheld
HH	Handheld
hp	Horsepower
INDP	In-Depth Investigations (CPSC database)
IPII	Injury/Potential Injury Incident (CPSC database)
IR	Infrared
ISO	International Standards Organization
kW	Kilowatt
LEV	Low Emission Vehicle
MAP	Manifold Absolute Pressure
MIL	Malfunction Indicator Light
NEISS	National Electronic Injury Surveillance System (CPSC database)
NIST	National Institute of Standards and Testing
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NOx	Oxides of nitrogen
NVFEL	National Vehicle and Fuel Emissions Laboratory
OB	Outboard
OEM	Original Equipment Manufacturers
OHV	Overhead Valve
OPEI	Outdoor Power Equipment Institute
Pd	Palladium
PGM	Platinum Group Metal
Ph2	Phase 2

Ph3	Phase 3
Pt	Platinum
PWC	Personal Water Craft
Rh	Rhodium
ROM	Ride On Mower
RPN	Risk Priority Number
SAE	Society of Automotive Engineers
SD/I	Sterndrive/Inboard
SI	Spark Ignition
SwRI	Southwest Research Institute
TDC	Top dead center
TPS	Throttle Position Sensor
UL	Underwriters Laboratory
US	United States
USDA	United States Department of Agriculture
USCG	United States Coast Guard
VR	Variable Reluctance
WBM	Walk Behind Mower
WOT	Wide open throttle
XLPE	Cross-link polyethylene

1. Introduction

A. BACKGROUND

Over the past 15 years, the Environmental Protection Agency (EPA) has implemented emission control programs for nonroad engines and equipment. Section 213 of the Clean Air Act (CAA) authorizes EPA to set emission standards for nonroad engines and equipment that “achieve the greatest degree of emissions reduction achievable through the application of technology which the Administrator determines will be available for the engines or vehicles to which such standards shall 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.” Section 216 of the CAA defines a nonroad engine as “an internal combustion engine (including the fuel system) that is not used in a motor vehicle or a vehicle used solely for competition.” Nonroad engines are used in a variety of nonroad vehicles and equipment and are primarily powered by diesel or gasoline. Gasoline-powered engines are frequently referred to as spark-ignition (SI) engines.

EPA’s nonroad program regulates nonroad engines and equipment in seven general engine categories. These categories are further divided into various subcategories or groups depending on what approach is most useful in distinguishing the particular product and application from others. For example, certain subcategories describe an engine’s or an equipment’s application (i.e. snowmobile, personal watercraft, nonhandheld equipment) while other subcategories include engines of a certain size (i.e. SI engines < 19kW (25hp)). Therefore, each of these seven engine categories contains further divisions, including engines and equipment with a wide range of horsepower or performance characteristics. Table 1-1 illustrates the nonroad program and its applicable regulations for these various subcategories.

Table 1-1 EPA Nonroad Engine Program

Engine Categories	Applicable Regulations	Date of Last Significant Rule	Code of Federal Regulation Citation	Applicable Standards
1. Locomotives engines	40 CFR Part 92	April 16, 1998	63 FR 18978	Exhaust
2. Marine diesel engines	40 CFR Part 94	December 29, 1999	64 FR 73300	Exhaust
3. Other nonroad diesel engines	40 CFR Parts 89, 1039	June 29, 2004	69 FR 38958	Exhaust
4. Marine SI engines	40 CFR Part 91	October 4, 1996	61 FR 52088	Exhaust
5. Recreational vehicle SI engines	40 CFR Part 1051	November 8, 2002	67 FR 68242	Exhaust & Evaporative
6. Small SI engines (SI engines ≤ 19 kW (or ≤ 30 kW if total displacement is ≤ 1 liter)) a. Handheld (HH) b. Nonhandhled (NHH)	40 CFR Part 90	a. Jan 12. 2004 b.Mar 30,1999	a. 69 FR 1824 b. 64 FR 15208	Exhaust
7. Large SI engines (SI engines > 19 kW (or > 30 kW if total displacement is ≤ 1 liter))	40 CFR Part 1048	November 8, 2002	67 FR 68242	Exhaust & Evaporative

Section 428(b) of the 2004 Omnibus Appropriations bill (PL 108-199) required EPA to consider new emission standards for nonroad SI engines under 50 horsepower (hp). For purposes of this discussion, 50 hp is about 37 kilowatts (kW). The first three categories in Table 1-1 are only diesel engines so they are not covered by the provisions. As shown below, the remaining four categories are all SI engines, with all or at least some or their product offerings below 50 hp.

Table 1-2 SI Engine HP Distribution

SI Engine Category	Engine Subcategory	Estimated % < 50 hp
Marine SI	Outboard	65
	Personal Watercraft	< 5
	Sterndrive/Inboard	0
Recreational SI	All Terrain Vehicle	100
	Off-Highway Motorcycle	100
	Snowmobile	2
Small SI	Handheld	100
	Nonhandheld	100
Large SI	None	40

Standards for Marine SI engines were last promulgated in 1996 and are presently ending their phase-in period. Recreational SI engine standards were promulgated in 2002, and are beginning their phase-in in 2006. Small SI engine standards for nonhandheld (NHH) engines (containing Classes I and II) were last promulgated in 1999 and finish their phase-in next year, 2007. Standards for handheld (HH) (containing Classes III-V) are catalyst-based in many cases and the implementation approach was revised in a 2004 technology review. These engines do not complete their phase-in until 2010. Finally, two phases of standards for Large SI engines were promulgated in 2002, with catalyst-based standards and a new test cycle required for 2007.

Based on its assessment of these categories, EPA intends to propose revisions to the emission standards for Marine SI engines and Small SI NHH engines and equipment for exhaust and evaporative controls and HH equipment for evaporative controls. Under section 205 of the appropriations bill funding EPA for fiscal year 2006 (section 205 of PL 109-54) EPA, in coordination with other appropriate federal agencies, must complete and publish a technical study analyzing the potential safety issues associated with the proposed standards for engines <50hp, including the risk of fire and burn to consumers. The technical study is to be completed and published before the publication of the notice of proposed rulemaking. This safety study satisfies the requirements of this provision and will also be part of the supporting information in the rulemaking.

The safety analysis for NHH exhaust emissions is presented in Chapters 3 through 8. The safety analysis for evaporative control requirements for NHH and HH are presented in Chapter 9 and for Marine SI requirements in Chapter 10. The proposed rule is also expected to include the first ever exhaust and evaporative emission standards for sterndrive/inboard (SD/I) engines and vessels as part of our authority under section 213. However, they are not addressed in this safety study as they are all over 50hp. The impact on safety of new standards for these engines and vessels will be addressed in the proposal.

As part of the assessment for the rulemaking, EPA evaluated the performance of the current technology for NHH engines and equipment (studies for HH and Marine SI were not conducted). EPA's initial efforts focused on developing a baseline for emissions and general engine performance so that we could assess the potential for new emission standards for engines and equipment in this category. This process involved laboratory and field evaluations of the current engines and equipment. As part of this assessment EPA also reviewed engineering information and data on existing engine designs and their emissions performance. Using information and experience gathered in this effort, EPA initiated a testing program designed to evaluate improvements to the emissions performance of these gasoline engines and to assess the potential safety impacts associated with the use of more advanced emission control technology.

The technology approaches assessed by EPA for meeting the new standards for Class I (< 225cc engine displacement) and Class II (≥225 cc) NHH engines include exhaust catalyst aftertreatment and improvements to engine and fuel system designs. In addition to its own testing and development effort, EPA also met with engine and equipment manufacturers to better understand their designs and technology and to determine the state of technological progress beyond EPA's Phase 2 standards. EPA's research, development, and testing evaluation efforts included laboratory and real world field assessments of potential technology applications. In the course of this work EPA conducted both thorough evaluations of laboratory and field emissions performance as well as separate assessments of safety issues. The engines EPA used for developing these improved emissions factors were maintained based on manufacturer specifications. Every engine in the field evaluation was maintained at a level at least as rigorous as called for in the manufacturer's requirements.

The central focus of our safety assessments for NHH engine exhaust standards has been to understand the potential incremental safety impact of the application of catalyst-based exhaust emission controls on Class I and Class II engines. EPA's engineering analysis of the safety of exhaust and evaporative emission controls for NHH and HH engines and equipment focused on five areas:

1. Engineering analysis and emission testing of current technology Class I and Class II engines and Class I and Class II engines with properly designed emission control systems capable of achieving exhaust emission reductions beyond the Phase 2 standards (catalyst-based advanced prototype systems).

2. Exhaust emission and safety assessment testing of Class I and Class II engines in both a stock configuration and equipped with advanced prototype emission control systems. Engines were tested both in the laboratory and in the field over a broad range of operating conditions; external exhaust system surface temperatures were measured using infrared thermal imaging while temperatures for lubricant, cylinder head and exhaust gases were measured using thermocouple probes.

3. Laboratory analysis of significant off-nominal operating conditions that were identified by engine manufacturers, original equipment manufacturers (OEMs), and EPA staff.

4. Assessment of the potential safety impacts of evaporative emission control requirements.

5. The completion of design Failure Mode and Effects Analyses (FMEA) for Class I and Class II engines used in walk-behind and ride-on mowers and three process FMEAs for consumer use of lawn equipment. These studies were conducted as an additional tool for identifying potential safety concerns in going from Phase 2 to potential Phase 3 standards.

With regard to marine SI, we focused on safety issues related to incorporating upgraded fuel systems and engine modifications for both outboard and personal watercraft engines. We also assessed the potential incremental safety impacts of evaporative emission control requirements for marine SI vessels.

B. OVERVIEW

The remainder of this report is comprised of nine chapters. Following this Introduction, Chapter 2 explains EPA's basic approach to its assessment of the safety issue. Chapters 3 through 8 address only NHH engines. Chapter 3 gives background on small SI NHH engine technology, the relevant applicable safety standards, in-use experience related to the safety concerns of interest. Chapter 4 describes the safety issues and concerns raised by the various parties and identified by EPA and identifies the scenarios to be assessed along with the causal factors. Chapter 5 describes in detail the test methods employed by EPA while Chapter 6 presents the results of the testing. Chapter 7 describes the design and process FMEAs conducted by Southwest Research Institute (SwRI) and discusses the safety results in the context of potential Phase 3 standards. Chapter 8 presents EPA's technical conclusions for the Small SI engine category by assessing the concerns identified in Chapter 4 in light of the technical information and analyses presented in Chapters 5 through 7. Chapter 9 addresses the evaporative control requirements for equipment powered by Small SI engines. Finally, Chapter 10 assesses the potential safety impact evaporative and exhaust emission standards for Marine SI engines and vessels as discussed above. The appendices to this report contain relevant data and technical information referred to in the text.

2. EPA's Approach to Assessment of the Safety Issue

A. SCOPE OF ASSESSMENT

As mandated by Section 205, this study addresses four subcategories of nonroad engines and equipment containing SI engines under 50 hp for which EPA intends to propose revisions to the emission standards. These two categories are commonly referred to as Small SI and Marine SI. As explained in Chapter 1, the four subcategories include HH and NHH, in the Small SI engine category, and outboard and personal watercraft engines (OB/PWC), in the Marine SI engine category. The study does not address the EPA categories where EPA is not intending to propose revisions to the emission standards. This study also does not address safety issues concerning Marine SI vessels powered by SD/I engines. EPA intends to propose exhaust and evaporative standards for this Marine SI subcategory. EPA will address any safety concerns related to SD/I requirements as part of the proposed rule.

For Small SI and Marine SI we are considering new exhaust and/or evaporative emission standards. With regard to the Small SI category we are considering new exhaust and evaporative standards for nonhandheld equipment and new evaporative standards for handheld equipment. For Marine SI engines we are considering new exhaust and evaporative standards for both outboard engines and personal watercraft.

B. THE SMALL SI ENGINE ASSESSMENT

The small SI engines and equipment that we considered in this study have been commercially marketed for over 50 years, are commonly found across the United States (US), and have relatively frequent usage. For example, EPA estimates that there are over 52 million residential and commercial walk behind lawn mowers and ride-on lawn, garden, and turf equipment in-use in the United States today. EPA estimates that these are used about 3 billion hours per year. Thus, there is a large amount of in-use experience with the performance of this equipment over time. As successive generations of engines and equipment have entered the marketplace there have been improvements to address consumer satisfaction, performance, safety, and emissions, among other factors. Over this time, consumers have had a variety of types of performance experiences with this equipment. In some cases problems are related to engine or equipment design while in others they are related to human interactions. It is not uncommon for both factors to contribute to a problem.

It is not the purpose of this study to review or generally assess safety or performance issues with current small SI engines and equipment in-use. This study instead looks at the incremental impact on safety of moving from current Phase 2 standards to new Phase 3 hydrocarbon plus oxides of nitrogen (HC+NOx) exhaust emission standards for nonhandheld Small SI Engines which are nominally a 35-40 percent reduction over current Phase 2 emission standards, as well as fuel evaporative emission control requirements for all Small SI engines Although it was necessary to understand the performance of Phase 2 products in order to fully characterize the baseline used for this incremental safety analysis, this study does not assess and does not draw any conclusions on what safety risks, if any, are presented by current equipment. Instead, EPA took current equipment as the baseline, and evaluated the incremental impact on safety of moving from this baseline to equipment applying more advanced emissions control technology. The study does not address any issues not related to the potential proposed rulemaking for small SI engines, such as concerns about carbon monoxide (CO) exposure or refueling problems related to portable gasoline containers.

C. MARINE SI ASSESSMENT

EPA intends to propose revisions to the exhaust and evaporative emission standards for Marine SI engines. As with Small SI engines, the study addresses the incremental impact on safety of going from the current EPA standards to the standards under consideration. The study addresses both outboard engines and personal watercraft.

3. Technical Background on Nonhandheld Engines

A. CURRENT TECHNOLOGY

The scope of this study included Class I and Class II engine systems, which relate to residential walk-behind and riding lawn mowers, respectively. Residential lawn mower equipment was chosen for the following reasons:

1. Lawn mowers and the closely-related category of lawn tractors represent the largest categories of equipment using Class I and Class II nonroad SI engines. EPA estimates that over 47 million walk-behind mowers and ride-on lawn and turf equipment are in-use in the US today.

2. These equipment types represent the majority of sales for Small SI engines.

3. CPSC data indicates that more thermal burn injuries associated with lawn mowers occur than with other NHH equipment; lawn mowers therefore represent the largest thermal burn risk for these classes of engines.

4. General findings regarding advanced emission control technologies for residential lawn and garden equipment carry over to commercial lawn and turf care equipment as well as to other NHH equipment using Class I and Class II engines. Lawn mower design and use characteristics pose unique safety implications not encountered by other NHH equipment using these engines (i.e. a mower deck collects debris during operation whereas a pressure washer collects no debris). Thus, other NHH equipment may employ similar advanced emission control technologies for meeting the proposed standards without a corresponding concern regarding the safety issues analyzed in this study.

Information in EPA's nonroad emissions model estimates suggests about 1.5 billion lawn mower use events per year for residential lawn care equipment.[1] Much of the equipment is typically operated and refueled by the general public. The equipment is operated under conditions where grass-clipping and similar debris are often present, particularly during side-discharge or mulching grass cutting operations. Refueling operations typically occur from portable containers with no automatic cut-off, and can result in fuel spillage.

Class I product, mostly walk-behind mowers, are produced by both integrated and non-integrated manufacturers. Integrated manufacturers make both the engine and equipment, non-integrated manufacturers make only one of the two. In almost all cases the fuel tank and muffler are part of the Class I engine when it leaves the engine manufacturer. Based on manufacturer estimates provided as part of EPA's emission certification program, there are about 14 million Class I and Class II engines produced per year. In Class II, which also has integrated and non-integrated manufacturers, it is not uncommon to have the fuel tank and/or muffler added by the equipment manufacturer. According to the Outdoor Power Equipment Institute (OPEI), there were about 9 million lawn and garden units produced in the 2005 model year with the remainder comprised primarily of pressure washers, generators, tillers, snow throwers, construction, and commercial equipment. Table 3-1 below shows the current Phase 2 emission standards for Class I and Class II engines.

Table 3-1 EPA Phase 2 Emission Standards[2]

Engine Class	HC+NOx Standard (g/kW-hr)	CO Standard (g/kW-hr)	Final Phase-In Year for Large Manufacturers	Regulatory Useful Life (hours)
Class I	16.1	610	2007	125,250, or 500
Class II	12.1	610	2005	250, 500, or 1000
Crankcase must be closed. The HC+NOx standards do not apply to engines used in snow equipment. Emission averaging is allowed to meet the HC+NOx standard. There are no evaporative emission control requirements for Class I or Class II. The useful life category is determined by the manufacturer.				

EPA evaluated the incremental change in key safety parameters for the modification of lawn mowers and lawn tractors from Phase 2 emissions compliance to meeting potential Phase 3 HC+NOx emission standards of 10.0 g/kW-hr for Class I and 8.0 g/kW-hr for Class II. These standards would be 35-40 percent more stringent than Phase 2 emission standards on Federal certification fuel. The Phase 3 standards would not change the CO emission standard for NHH engines.

The potential Phase 3 emission standards would also include measures for controlling fuel evaporative emission requirements. While we looked at the full range of potential evaporative controls, our present program is focused on fuel tank and fuel hose permeation emissions, running loss controls, and diffusion losses from freely vented fuel caps. The fuel systems for Class I and Class II equipment consist of rubber fuel hoses and open-vented fuel tanks which may be constructed out of metal or plastic. Based on information supplied by manufacturers we estimate that about 80 percent of Class I and 90 percent of Class II equipment are equipped with plastic fuel tanks. Fuel hoses used today are typically made out of inexpensive nitrile rubber and there are general industry consensus performance standards related to hoses which apply.

The following discussion explains the design elements for the type of emission control technology that could be used to achieve the potential Phase 3 emission standards discussed above. These technical discussions and information presented below are derived from more than two years of laboratory and field work conducted by EPA in assessing current Phase 2 engine technology and developing prototype Phase 3 systems.

The North American automotive market is now entering its fourth decade of high-volume production of exhaust catalysts for light-duty gasoline-powered vehicles since the introduction of catalysts on Chrysler vehicles in 1975. With the advent of Federal Tier 2 and California Low Emission Vehicle (LEV) II exhaust emission standards, light-duty and medium-duty vehicles are equipped with catalysts and engine management systems that control NOx, HC, and CO emissions with greater than 99 percent efficiency relative to previous, non-catalyst engines.

Class I and Class II nonroad SI engines face a number of engineering, safety, and cost challenges that can differ substantially from those of light duty automotive applications. As a result, Class I and Class II exhaust emission control systems differ from that of light-duty gasoline vehicles but share some common elements with emission control systems that are now being applied to small-displacement on-highway motorcycles.

In addition, Class I and II equipment can make use of the advances in materials technology and fuel system designs that have been made in the automotive industry over the past several decades. These approaches to improved fuel containment are now being applied to other nonroad applications in anticipation of upcoming evaporative emission standards.

Class I engines

Class I engines typically are equipped with integral exhaust and fuel systems and are air-cooled. Significant applications include walk-behind lawn mowers (largest segment), pressure washers, generator sets and pumps. There are both overhead valve (OHV) and side-valve (SV) engines used in Class I, but side-valve engines are the predominant type in Class I, particularly in lawn mower applications. They currently represent about 60 percent of Class I sales. Exhaust catalyst design for Class I engines must take into account several important factors that differ from automotive applications:

1. Air-cooled engines run rich of stoichiometry to prevent overheating when under load. Because of this, CO and HC emissions can be high. Catalyst induced oxidation of a high percentage of available reactants in the exhaust in the presence of excess oxygen (i.e., lean of stoichiometric conditions) can result in highly exothermic exhaust reactions and increase heat rejection from the exhaust. For example, approximately 80 to 90 percent of the energy available from catalyst-promoted exhaust reactions is via oxidation of CO.

2. Air-cooled engines have significant HC and NOx emissions that are typically much higher on a brake-specific basis than water-cooled automotive engine types. Net heat available from HC oxidation and NOx reduction at rich of stoichiometric conditions is considerably less than that of oxidation of CO at near stoichiometric or lean of stoichiometric conditions due to the much lower concentrations of NO and HC in the exhaust relative to CO.

3. Most Class I engines do not have 12-volt DC electrical systems to power auxiliaries and instead are pull start. Electronic controls relying on 12-volt DC power would be difficult to integrate onto Class I engines without a significant cost increase.

4. Most Class I engines use inexpensive stamped mufflers with internal baffles. Mufflers are typically integrated onto the engine and may or may not be placed in the path of cooling air from the cooling fan.

5. The regulatory emission test cycles (A-cycle, B-cycle), manufacturer's durability cycles and some limited in-use operation data indicate that emissions control should focus primarily on light and part load operation.

These factors would lead to exhaust catalyst designs for small engines that should differ somewhat from those of light duty gasoline vehicle exhaust catalysts. Design elements specific to Class I Phase 3 exhaust catalysts would include:

1. Catalyst substrate volume would be sized relatively small so as to be space-velocity limited. Catalyst volume for Class I Phase 3 engines would be approximately 10 to 25 percent of the engine cylinder displacement, depending on cell count, engine-out emission levels, and oil consumption. Catalyst substrate sizes would be compact, with typical catalyst substrate volumes of approximately 1 to 3 cubic inches. This would effectively limit mass transport to catalyst sites at moderate-to-high load conditions and reduce exothermic reactions occurring when exhaust temperature is highest. This is nearly the opposite of the case of typical automotive catalyst designs. Automotive catalyst volume is typically 50 to 100 percent of cylinder displacement, with the chief constraints on catalyst volume being packaging and cold-start light-off performance.

2. Catalyst precious metal loading (Pt-platinum, Pd-palladium, Rh-rhodium) would be kept relatively low, and formulations would favor NOx and HC selectivity over CO selectivity. We estimate that typical loading ratios for Phase 3 would be approximately in the range of 30 to 50 g/ft3 (approximately 50 percent of typical automotive loadings at light-duty vehicle Tier 2 emission levels) and can be Pt:Rh, Pd:Rh or tri-metallic. Tri-metallic platinum group metal (PGM) loadings that replace a significant fraction of Pt with Pd would be less selective for CO oxidation and would also reduce the cost of the catalyst. Loading ratios would be similar or higher in Rh than what is typically used for automotive applications (20-25 percent of the total PGM mass in small SI) to improve NOx selectivity, improve rich of stoichiometry HC reactions and reduce CO selectivity.

3. Catalysts would be integrated into the muffler design. Incorporating the catalyst into the muffler would reduce surface temperatures, and would provide more surface area for heat rejection. This is nearly the opposite of design practice used for automotive systems, which generally try to limit heat rejection to improve cold-start light-off performance. The design for Class I Phase 3 engines would have somewhat higher surface area and somewhat larger volume than many current Class I muffler designs in order to promote exhaust heat rejection and to package the catalyst, but would be similar to some higher-end "quiet" Class I muffler designs. Appropriately positioned stamped heat-shielding and touch guards would be integrated into Class I Phase 3 catalyst-muffler designs in a manner similar to many Class I Phase 2 mufflers. A degree of heat rejection would be available via forced convection from the cooling fan, downstream of cooling for the cylinder and cylinder head. This is the case with many current muffler designs. Heat rejection to catalyst muffler surfaces to minimize "hot spots" can also be enhanced internally by turning the flow through multiple chambers and baffles that serve as sound attenuation within the muffler, similar to the designs used with catalyst-equipped lawn mowers sold in Sweden and Germany.

4. Many Class I Phase 3 catalysts would include passive secondary air injection to enhance catalyst efficiency and allow the use of smaller catalyst volumes. Incorporation of passive secondary air allows halving of catalyst substrate volume for the same catalyst efficiency over the regulatory cycle. A system for Class I Phase 3 engines would be sized small enough to provide minimal change in exhaust stoichiometry at high load conditions so as to limit heat rejection, but would be provide approximately 0.5 to 1.0 points of air-to-fuel ratio change at conditions of 50 percent of peak torque and below in order to lower HC emissions effectively in engines operating at air-to-fuel ratios similar to those of current Class I Phase 2 engines. Passive secondary air systems are preferred. Mechanical or electrical air pumps are not necessary. Passive systems include stamped or drawn venturis or ejectors integrated into the muffler, some of which may incorporate an air check-valve, depending on the application. Pulse-air injection is also a form of passive secondary air injection. Pulse air draws air into the exhaust port through a check-valve immediately following the closure of the exhaust valve. Active secondary air (air pump) systems were not considered in this analysis since they may be cost prohibitive for use in Class I applications due to the need for a mechanical accessory drive or 12-volt DC power.

5. Class I engines are typically turned off via a simple circuit that grounds the input side of the ignition coil. Temperature fail-safe capability would, if appropriate, can be incorporated into the engine by installing a bimetal thermal switch in parallel with the ignition grounding circuit used for turning the engine off. The switch can be of the inexpensive bimetal disc type in wide-spread use in numerous consumer products (furnaces, water-heaters, ovens, hair dryers, etc.). To reduce cost, the bimetal switch could be a non-contact switch mounted to the engine immediately behind the muffler, similar to the installation of bimetal sensors currently used to actuate automatic chokes on current Phase 2 Class I lawn mower engines.

Class II engines

Almost all Class II engines are air-cooled. Unlike Class I engines, Class II engines are not typically equipped with integral exhaust systems and fuel tanks. Significant applications include lawn tractors (largest segment), commercial turf equipment, generator sets and pumps. Overhead valve engines have largely replaced side-valve engines in Class II, with the few remaining side-valve engines certifying to the Phase II standards using emissions credits or being used in snow thrower type applications where the HC+NOx standards do not apply. Class II engines are typically built more robustly than Class I engines. They often use cast-iron cylinder liners, may use either splash lubrication or full-pressure lubrication, employ high volume cooling fans and in some cases, use significant shrouding to direct cooling air. Exhaust catalyst design practice for Class II engines will differ depending on the level of emission control. Class II engine designs are more suitable for higher-efficiency emission control systems than most Class I engine designs. The design factors are somewhat similar to Class I:

1. Class II engines are mostly air-cooled, and thus must run rich of stoichiometry at high loads. The ability to operate at air-to-fuel ratios rich of stoichiometry at high load may be more critical for some Class II engines than for Class I engines due to the longer useful life requirements in Class II. The engines incorporate more advanced fuel metering and spark control than is typical in Class I, in order to meet the more stringent Class II Phase 2 emission standards (12.1 g/kW-hr HC+NOx in Class II versus 16.1 g/kW-

hr in Class I). The heat energy available from CO oxidation is typically somewhat less than the case in Class I because of slightly lower average emission rates.

2. As with Class I engines, air-cooled Class II engines have significant HC and NOx emissions that are typically much higher on a brake-specific basis than water-cooled automotive engine types, but generally with a somewhat higher fraction of NOx in the total regulated HC+NOx emissions and lower CO emissions than is the case for Class I engines.

3. Most Class II engines are equipped with 12-volt DC electrical systems for starting. Electronic controls relying on 12-volt DC power could be integrated into Class II engine designs. Low-cost electronic engine management systems are extensively used in motor scooter applications in Europe and Asia. Both Kohler and Honda have introduced Class II engines in North America that use electronic engine management systems.

4. Class II engines use inexpensive stamped mufflers with internal baffles similar to Class I, but the mufflers are often not integrated onto the engine design and may be remote mounted in a manner more typical of automotive mufflers. Class II mufflers are often not placed in the direct path of cooling air from the cooling fan.

5. As with Class I, the regulatory cycles (A-cycle, B-cycle), manufacturer's durability cycles and some limited in-use operation data indicate that emissions control should focus primarily on light and part load operation.

Taking these factors into account would point towards exhaust catalyst designs that differ from those of light duty gasoline exhaust catalysts and differ in some cases from Class I systems. Elements specific to Class II Phase 3 emission control system design using carburetor fuel systems would include:

1. Catalyst substrate volume would be sized relatively small so as to be space-velocity limited. Catalyst volume for Class II Phase 3 engines would be approximately 33-50 percent of the engine cylinder displacement, depending on cell count, engine-out emission levels, oil consumption and the useful life hours to which the engine's emissions are certified. Catalyst substrate sizes would be very compact within typical mufflers used in Class II, with typical catalyst substrate volumes of approximately 3 to 12 cubic inches. This would effectively limit mass transport to catalyst sites at moderate-to-high load conditions and reduce exothermic reactions occurring when exhaust temperature is highest.

2. Catalyst precious metal loading would be kept relatively low, and formulations would favor NOx and HC selectivity over CO selectivity to minimize heat concerns. We estimate that typical loading ratios for Phase 3 would be approximately in the range of 30 to 50 g/ft3 (approximately 50 percent of typical automotive loadings) and could be Pt:Rh, Pd:Rh or tri-metallic. Tri-metallic PGM loadings that replace a significant fraction of Pt with Pd would be less selective for CO oxidation and would also reduce the cost of the catalyst. Loading ratios would be similar or higher in Rh than what is typically used for automotive applications (20-25 percent of the total PGM mass in small SI).

3. Catalysts would be integrated into the muffler design. Incorporating the catalyst into the muffler would reduce surface temperatures relative to the use of a separate catalyst component. The catalyst for Class II Phase 3 engines would be integrated into mufflers that are similar in volume to today's Class II Phase 2 mufflers. Appropriately positioned stamped heat-shielding and touch guards would be integrated into Class II Phase 3 catalyst-muffler designs in a manner similar to current product. Class II engines typically have a much higher volume of cooling air available downstream of the cylinder than Class I engines. Heat rejection from the cylinder and cylinder head increases the temperature of the cooling air, but it is still sufficiently below the temperature of exhaust system components to allow its use for forced cooling. Thus a degree of heat rejection would be available via forced convective cooling of exhaust components via the cooling fan. However, this would require some additional ducting to supply cooling air to exhaust system surfaces along with careful layout of engine and exhaust components within the design of the equipment that it is used to power. Integrated catalyst-mufflers can also use exhaust energy for ejector cooling (see

chapter 6). Heat rejection to catalyst muffler surfaces to minimize “hot spots” can also be enhanced internally by turning the flow through multiple chambers and baffles that serve as sound attenuation within the muffler.

4. Some applications may include secondary air injection to enhance catalyst efficiency. Incorporation of passive secondary air allows halving of catalyst substrate volume for the same catalyst efficiency over the regulatory cycle. In many cases, this may not be necessary due to the lower engine-out emissions of Class II engines. In cases where secondary air is used, it could either be a passive system similar to the previously described Class I systems, or an active system with an engine driven pump. Pump drive for active systems could be either 12-volt DC electric or via crankcase pulse, and pump actuation could be actively controlled using an electric solenoid or solenoid valve. The use of active systems is an option but seems unlikely.

5. Class II engines are typically turned off via a simple circuit that grounds the input side of the ignition coil. As with Class I engines temperature fail-safe capability could be incorporated into the engine by installing a bimetal thermal switch in parallel with the ignition grounding circuit used for turning the engine off, although application of this may not be suitable for use with ride-on equipment.

6. Higher catalyst efficiency, considerably lower exhaust emissions levels, and improved fuel consumption are possible with Class II engines, but temperature considerations might necessitate the use of electronic engine management and open-loop fuel injections systems. In such a case, the design and integration of the emission control system would more closely resemble automotive applications, but still with some differences.

Elements specific to Class II Phase 3 emission control system design using electronic engine management to reduce emissions beyond the nominal 35 percent reduction target would include:

1. Electronic fuel and spark control. Fuel metering would be via a low-cost open-loop fuel injection system similar to systems currently in production for motor scooters in Europe and Asia. Such systems use far fewer sensors and components and simpler Engine Control Units (ECU) than typical automotive applications. Open loop fuel mapping can be based on feedback of manifold absolute pressure (MAP) and engine oil temperature, with injection timing based on a magnetic signal from the flywheel or an inductive signal from the ignition system. Air-to-fuel ratio and spark timing can also be tailored at moderate to light-load conditions to favor engine-out control of HC and CO emissions while still operating sufficiently rich of stoichiometry to allow good NOx conversion over the catalyst. Such a control strategy would reduce heat rejection from the catalyst and provide improved engine protection and reduced exhaust temperature at high-load conditions. Secondary air injection into the exhaust would not be necessary.

2. Larger catalyst volume with higher precious metal loading. Improved air-to-fuel ratio and spark control allows the use of larger catalyst volumes (50 to 75 percent of engine displacement) with a higher precious metal loading than is possible with carbureted engines that have higher engine-out CO levels at light to moderate loads. The advanced engine control system discussed in item 1 above would reduce engine out CO emissions and thus catalyst exotherms related to further CO oxidation.

3. Catalysts integrated into the muffler design. Catalysts would be integrated into mufflers similar in design to the systems described for carbureted Class II engines. Muffler volume would be similar to existing designs.

4. Misfire detection software would be integrated into the ECU that could:

    a. notify the user that engine servicing is necessary via illumination of a malfunction indicator light (MIL);

    b. place the engine in a “limp mode” in the event that an engine operating condition is encountered that has potential safety, engine durability, or emission control system durability implications:

c. could shut-down the engine under extreme circumstances.

d. ECU software could also integrate an input from a bimetal thermal switch for MIL illumination, "limp mode" initiation, or engine shut-down.

B. CURRENT SAFETY STANDARDS

An appendix to the SwRI report lists over 30 mandatory and voluntary standards which are, to varying degrees, applicable to small SI equipment and in some cases specifically to nonhandheld engines.[a] The majority of these are voluntary American National Standards Institute (ANSI) and Society of Automotive Engineers (SAE) standards. US Department of Agriculture (USDA) requirements are primarily applicable to handheld equipment such as chainsaws. American Society of Agricultural Engineers (ASAE), International Standards Organization (ISO), and the American Society for Testing and Materials (ASTM) all have surface temperature requirements.

The existing ANSI standards for turf care equipment standards are sponsored by the Outdoor Power Equipment Institute. These ANSI standards address engine and equipment safety for small gasoline engines. The predominant standards followed by the Class I and Class II engine and equipment manufacturers are ANSI B71.1, American National Standard for Consumer Turf Care Equipment-Walk-Behind Mowers and Ride-On Machines with Mowers-Safety Specifications and ANSI B71.4, American National Standard for Commercial Turf Care Equipment – Safety Specification for Consumer Lawn Care and Commercial Lawn Care Equipment.[3,4] They are designed to address operator and by-stander safety. The ANSI standards apply to the engine and exhaust system as well as the complete equipment product. Within the ANSI standards for residential lawn care equipment, there are three sections that discuss touch burn safety and prevention of fuel ignition during refueling, with two sections referring to walk-behind mowers and one section referring to ride-on lawn equipment.

- From ANSI B 71.1, Part II: Walk-Behind Mowers: ,American National Standard for Consumer Turf Care Equipment-Walk-Behind Mowers and Ride-On Machines with Mowers-Safety Specifications, Part II: Walk-Behind Mowers:
    - "5.2 Heat protection - A guard or shield shall be provided to prevent inadvertent contact with any exposed components that are hot and may cause burns during normal starting and operation of the machine."
    - "5.3 Fuel ignition protection - Overflow gasoline shall be diverted away from the muffler outlet area."
- From ANSI B 71.1, Part III: Ride-on mowers, lever steer mowers, lawn tractors, and lawn and garden tractors:
    - "15.2 Heat protection - A guard or shield shall be provided to prevent inadvertent contact with any exposed components that are hot and may cause burns during normal starting, mounting, and operation of the machine."
- From ANSI B 71.4, Figure 3, American National Standard for Commercial Turf Care Equipment – Safety Specification, In section 4.2.4, Operation, Service, Maintenance Instruction (figure 3), the following information is required in the instruction manual:
    - Clean grass and debris from cutting units, drives, mufflers, and engine to help prevent fires. Clean up oil or fuel spillage.
    - Let engine cool before storing and do not store near flame.

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[a] The SwRI report and its appendices are in located in Appendix C of this study.

  - Shut off fuel while storing or transporting. Do not store fuel near flames or drain indoors.

In general these ANSI standards primarily focus on safety labeling, operator instructions, manuals, and a series of safety tests regarding equipment operation, mower deck safety, prevention of ejection of objects from the deck and equipment maneuverability. No design standards or surface temperature criteria are specified, nor are standardized test procedures provided for fire or touch burn safety for lawn care equipment. There are no ANSI standards specific to fuel tanks or fuel hoses.

- ASAE Standard S440.3 Safety for Powered Lawn and Garden Equipment[5] addresses hot surfaces in section 9 stating:

  - 9.1.7 Hot surfaces (engine, hydraulic, transmission, etc) that exceed a temperature of 90°C (194°F) for nonmetallic surfaces, or 80°C (176°F) for metallic parts while operating at 21°C (70°F), except surfaces of equipment intended primarily for winter use, which shall be at 5°C (41°F). All surfaces which exceed 65.5°C (150°F) at 21°C (70°F) ambient and which might be contacted by the operator during normal starting, mounting, operating, or refueling shall be indicated by a safety sign located on or adjacent to the surface.

- ISO standard 5395 section 2.2.3 addresses heat protection stating[6]:

  - A guard or shield shall be provided to prevent accidental contact with any exposed engine exhaust components greater than 10 cm^2 and with a hot surface temperature greater than 80° C at 20° C (+/- 3°C) ambient temperature during normal operation of the machine.

- ASTM Standard C1055-03, the Standard Guide for Heated System Surface Conditions that Produce Contact Burn Injuries recommends first determining the acceptable contact time and level of burn severity[7]. They list an acceptable contact time of 5 seconds for industrial processes and 60 seconds for consumer items. The maximum operating surface temperature can then be derived from two equations given in the standard. A recommendation to install jacketing or insulation is made if the injury level exceeds the chosen criteria; a redesign to the system is recommended if the criteria still cannot be met after installing protective measures. Nominally a value of 70°C is established as a level above which action is necessary.

The CPSC issued a regulation, 16 CFR Part 1205, to prevent users and bystanders from coming into contact with mower blades[8]. There are no Federal regulations, standards, or test procedures related to addressing fire or burn risk with residential lawn equipment.

There are machine standards for noise and other operator and by-stander impacting characteristics in the European Machinery Directives. These machine standards are referred to during the engine design process. Most of the machine standards focus on the safety of the cutting blades. There are also installed engine operating tests designed to address heat exposure of stationary or parked tractors. These specifically focus on grass browning and surface temperature tests. These tests involve dumping the engine load and either letting the engine idle for two to three minutes or shutting the engine off. These tests are typically designed to address the level of distress caused to the grass.

There are a range of threshold temperature specifications that equipment manufacturers require of their engine suppliers for surface temperatures and exhaust temperatures. Most temperature requirements are for functionality rather than for safety. These include issues related to ventilation, tire side wall heating (for exhaust exiting near the rubber front tires), and oil degradation protection.

In the same vein, it should be noted that in discussions with EPA all engine and equipment manufacturers indicated that they have various proprietary tests they use to address in-use safety. These are applied when engines and fuel systems are completed by the original engine manufacturer, and it is often the case that the engine manufacturer works with and advises the equipment manufacturer on safety specifications and requirements for the safe application of engines, mufflers, and fuel tanks as appropriate.

C. IN-USE SAFETY EXPERIENCE

Assessing incremental impact on safety risk from applying more advanced emission control technology requires a thorough understanding of the problems and in-use safety experience with current products. To conduct this assessment EPA coordinated closely with CPSC. The staff of CPSC provided copies of relevant CPSC technical reports and provided detail and synopses of relevant information from four key databases. EPA also reviewed CPSC's public website which contained information on voluntary recall actions.

The technical reports provided by CPSC include the following:

- U.S. Consumer Product Safety Commission. (2004). Hazard Analysis of Power Lawn Mower Studies Calendar Years 2003 and 1993. Washington DC: Adler, P.; Schroeder, T.[9]

  This report examined data collected from 1983 through 1993 to evaluate the effectiveness of the mandatory standard addressing blade contact injuries and the ride mower portion of the voluntary ANSI/OPEI B71.1. Blade-contact and thrown object hazards were examined with walk behind and ride-on mowers. Additionally, rolling/tipping over hazard was examined in ride-on mowers. All other hazards, including hot surfaces contact and fire/flame, were categorized as 'other' and were not further addressed by this report.

- U.S. Consumer Product Safety Commission. (2003). Hazard Screening Report Yard and Garden Equipment (Product Codes 1400-1464). Washington DC: Rutherford, G., Marcy, N., Mills, A.[10]

  This report compared the risk of different products within the Yard and Garden Equipment category based on 2001 injury data and 2000 death data. Lawn mowers represented the largest cost associated with injury and deaths. A common hazard among all yard and garden equipment was a leaking fuel system which was mostly reported with riding mowers and walk behind mowers. No further information was given specific to lawn mowers.

- U.S. Consumer Product Safety Commission. (1993). Ride-On Mower Hazard Analysis (1987-1990). Washington DC: Adler, P.[11]

  This report provides a detailed hazard analysis of lawn mowers for reporting periods 1987-1990; a comparison was made with lawn mower hazard patterns from 1983-1986. Table 6 indicates that for the periods 1983-86 and 1987-90, 5-6 percent of all injuries associated with ride-on mowers treated in US hospital emergency rooms are burns. Lacerations and burns from a hot surface contact occurred to hands and accounted for 77 percent of all hand injuries.

- U.S. Consumer Product Safety Commission. (1993). Deaths Related to Ride-On Mowers: 1987-1990. Washington DC: David, J. A.[12]

  A follow-up report to CPSC Rider-On Mower Hazard Analysis (1987-1990) indicates that for the period 1987-1990, 2.5 percent of deaths were fire-related and indicates the fraction of fire-related hospital emergency room visits to be five percent for 1983-1986 and two percent for 1987-1990., There are approximately 850 hospital visits related to touching hot surfaces, and nine deaths related to fire for ride-on mowers for the period 1987-1990. It should be noted that these figures cover only ride-on mowers.

- U.S. Consumer Product Safety Commission. (1988). Hazard Analysis, Ride-On Mowers. Washington DC: Smith, E.[13]

This report gives an estimated 6 percent of in-use injuries as being thermal-burn related, such as a hot muffler or exhaust pipe. In most cases the engine was reported as being off, but the mower was still in use, which can include making repairs, maintenance, fueling, getting on/off, lifting, pushing, or other.

- U.S. Consumer Product Safety Commission. Thermal Burn Contact-Related Injuries Associated with Gasoline-Engine Powered Equipment, 1990-1998t. Washington DC: Adler, P.[14]

  This report discusses thermal burns exclusively from contact related injuries on gasoline engine powered equipment for the period 1990 – 1998. This report discusses gasoline engine powered equipment such as walk behind and riding mowers, chainsaws, rotary tillers, brush cutters. A contact burn injury is characterized by inadvertent contact with hot components or surfaces on the equipment. Based on the National Electronic Injury Surveillance System (NEISS) database there were an estimated average of 2,200 contact burn injuries treated in U.S. hospital emergency rooms during the 9 year period. Of these, 17 percent were related to the lower arm/leg and 68 percent were on the hand or finger. First and second degree burns are 53 percent of the total. Table 3 of this report indicates that 41 percent of burns were related to the muffler, 13 percent related to the exhaust tailpipe, 13 percent related to engine components, and 33 percent related to other surfaces. Muffler contact thermal burns were the dominant risk in all the engine-powered equipment discussed in this report.

In addition, CPSC provided EPA focused extracts related to fire and burn incidents from four different databases.

1. CPSC's NEISS database is comprised of a sample of hospitals that are statistically representative of hospital emergency rooms nationwide. From the data collected, estimates can be made of the numbers of injuries associated with consumer products and treated in hospital emergency departments.

2. CPSC's Injury/Potential Injury Incident File (IPII) contains summaries, indexed by consumer product, of Hotline reports, product-related newspaper accounts, reports from medical examiners, and letters to CPSC.

3. CPSC's In-Depth Investigations (INDP) file contains summaries of reports of investigations into events surrounding product-related injuries or incidents. Based on victim/witness interviews, the reports provide details about incident sequence, human behavior, and product involvement.

4. The National Fire Incident Reporting System (NFIRS) is a database of fires attended by the fire service. NFIRS provides data at the product level and is not a probability sample. The information from the NFIRS database results are weighted up to the National Fire Protection Association (NFPA) survey to provide national annual product-level estimates.

US CPSC's public website contains information on voluntary manufacturer recalls dating back over 30 years. In reviewing this website, EPA reviewed recalls related to small gasoline-powered equipment such as lawn mowers, generators, pumps, pressure washers, utility vehicles, snow throwers, go-karts, tractors, and engines. In these nine categories, EPA identified 32 recall actions that were related to either fire or burn risk on gasoline-powered equipment.

CPSC Databases:

Working closely with CPSC staff, EPA reviewed the databases and recall events to identify those which might have a bearing on this safety study. Each of these is discussed below.

NEISS: CPSC's National Electronic Injury Surveillance System reported a total of 475 thermal burn injuries related to gasoline-fueled lawn mowers that were treated in hospital emergency rooms over the five year period 2000-2004.[15] The product codes used to create this dataset included walk behind mowers, riding lawn mowers, lawn tractors and lawn mower product codes that do not specify the type of mower. Based on this period sampling of NEISS reported cases, there were an estimated 19,072 lawn mower thermal burns injuries treated in emergency rooms around the United States. Ninety six percent of these injuries were treated and released. Most of the victims

(51%) suffered hand injuries. Other body parts that were injured frequently were finger, lower arm, and lower leg (about 15%, 13%, and 8% of the cases, respectively).

The descriptive narratives of the NEISS reported cases were reviewed to determine hazard patterns that resulted in thermal burn injuries. The following hazard patterns were identified:

- Contact Burn: An individual contacts a hot lawn mower component and receives a burn.
- Refueling-Related Fire: Ignition of fuel vapor when an individual was refueling.

In addition, there were two NEISS hazard patterns (shown below) which either had a significant user behavior component to the problem, which is not a technical issue, or were inadequately described in the records to allow a laboratory or field assessment of the incremental risk. These two items are assessed primarily in the FMEA.

- Unspecified: The running lawn mower caught fire/exploded for reasons unspecified.
- Maintenance: An individual is performing lawn mower maintenance activities when a fire occurs.

Table 3.2 shows the annual NEISS estimates for both thermal burn injuries associated with gasoline fueled lawn mowing equipment from 2000-2004 and the portion of these burns that were due to the victim contacting a hot lawn mower component. There was an estimated average of 3,814 thermal burn injuries per year[b] with contact burns accounting for 88% (3,375) of these injuries. There were no significant differences among the years studied, nor were there any significant trends detected over these five years.

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[b] Note: The 2000-2004 NEISS estimates are larger than the 1990 – 1998 estimates in report 6, [*Thermal Burn Contact-Related Injuries Associated with Gasoline-Engine Powered Equipment, 1990-1998,* Adler, P., because the 2000-2004 data set included additional product codes such as lawn mowers not specified, tractors other or not specified, powered lawn mowers not specified.

Table 3-2
Annual Estimates of Emergency Room Treated Thermal
Burns From Gasoline-Fueled Lawn Mowing Equipment[16]

Year	Estimate of Thermal Burn Injuries	Proportion of Thermal Burn Injuries due to Contact
2000	3,509	92% (3,236)
2001	4,256	85% (3,626)
2002	4,354	92% (3,985)
2003	3,587	84% (3,026)
2004	3,365	89% (3,002)
Total	19,072	88% (16,875)
Mean	3,814	88% (3,375)

IPII and INDP: Gasoline-powered lawn mower records related to thermal burn injuries or potential injuries were obtained from CPSC's Injury/Potential Injury Incident File and In-Depth Investigation files.[17] For the five year period of January 2000 through December 2004, there were 466 IPII records and 87 INDP records. There were cases of some duplication in the NEISS, IPII/INDP records because the emphasis was in finding scenarios that can lead to thermal burn injuries rather than removing duplicate records. EPA and CPSC reviewed every record in these databases, with the purpose of identifying the prevalence of problems with engine or equipment systems affected by EPA's potential new exhaust and fuel evaporative emission standards. Several hazard patterns were identified from the INDP and IPII records that caused or could potentially cause fire and thermal burn injuries. These hazard patterns fall into two basic categories. In the first, the hazards identified are directly traceable to a technical performance or failure in a component or subsystem on the engine or are the effect of the characteristics and performance of the equipment itself. These are shown below:

- Fuel Leaks: fuel leaks from tank installed on equipment, faulty fuel hose or primer bulb, or from faulty or malfunctioning carburetor
- Debris Fire: Ignition of grass or leaves from hot components on the lawn mower
- Shutdown/Storage: A lawn mower stored or used near combustibles/flammable materials or near an ignition source such as an appliance with a pilot light results in a fire.
- Engine Backfire/Misfire: The lawn mower backfires resulting in either noise or fire/flames.
- Contact Burn: An individual contacting a hot lawn mower component that results in a burn
- Refueling Related Fire: Ignition of fuel liquid or vapor related to refueling

In addition, there were three hazard patterns (shown below) which either had a significant user behavior component to the problem which is not a technical issue or were inadequately described in the records to allow a laboratory or field assessment of the incremental risk. These three items are assessed primarily in the FMEA.

- Maintenance: An individual performing lawn mower maintenance activities that results in a fire
- Tip Over: A riding lawn mower tips over when in use resulting in fuel leaks. It is believed that fuel leaks from the overturned lawn mower are primarily from the vented gas cap or from the carburetor. In some of these records, the individual becomes trapped under the riding lawn mower.
- Unspecified: For reasons unspecified, the running lawn mower catches fire/explodes

NFIRS: The National Fire Incident Reporting System is based on firefighter and first responder reports on incidents to which they respond. The data compiled by the US Fire Administration and the National Fire Protection Association is not as complete or precise as that from the NEISS. Nonetheless, the data provided by CPSC estimates that for 2002 there were 100 fires involving gasoline-fueled lawn mowing equipment and estimates that there were 10 injuries associated with these fires.[18]

CPSC RECALL INFORMATION

The CPSC website publishes Recalls and Product Safety News, where manufacturers, in cooperation with CPSC, voluntarily recall products that pose a safety hazard to consumers.[19] Recall notices published during the period of January 2000 to December 2004 were reviewed. During this period there were a total of 22 lawn mowers or lawn mower engine recalls due to safety issues related to fire and thermal burn injuries. These 22 recall notices affected approximately 850,000 lawn mower units. Table 3-3 identifies the following hazard patterns from the recall notices:

Table 3-3: Fire/Burn Risk Related Recall Events for Small Gasoline-powered Lawn/Garden Equipment

Problem Category	Number Recalls	Years Issued	Years Affected	Incidents Reported	Total Equipment Involved
Fuel Tank Leaks	11	2000-2004	1995-2004	2229	742,054
Fuel Hose Leaks	5	2000-2004	2001-2004	5	4660
Backfire (Misfire)	2	2002	1998-2001	25	34,000
Refueling Vapor Ignition	1	2001	1998-2001	28	39,000
Other	3	2000-2004	1999-2003	27	28,300

EPA also identified about 10 other CPSC recalls related to small engines which either were not applicable to lawn and garden equipment or occurred outside of the five year evaluation period. Most of these were related to fuel tanks and fuel hoses. This type of problem was also identified in the 2000-2004 lawn mower equipment recalls.

Discussion of CPSC Data

Taken as a whole, the reports and data provided by CPSC are consistent and indicate that the following types of incidents should be of primary technical concern when evaluating the incremental impact on safety of the more advanced emissions control technology: burns due to contact with hot surfaces, fuel tank leaks, fuel hose leaks, refueling vapor ignition, debris fires, shutdown and storage related fires, engine backfire/misfire, and carburetor fuel leaks.

In the chapters which follow, EPA identifies causative factors which might be contributing to these hazard patterns and their occurrence in use, and presents data and technical analyses assessing the incremental impact on these hazard patterns of potential Phase 3 exhaust and fuel evaporative emission standards for Class I and Class II engines and equipment.

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[1] "Estimated Number of Refueling Events for Residential Mowing Equipment," EPA memorandum from Phil Carlson, March 3, 2006, Docket EPA-HQ-OAR-2004-0008-0331.

[2] U.S. Code of Federal Regulations, Title 40, Part 90, §90.103, Tables 2 and 3.

[3] ANSI B71.1-2003, "American National Standard for Consumer Turf Care Equipment – Walk-Behind Mowers and Ride-On Machines with Mowers – Safety Specifications", American National Standards Institute, 2003.

[4] ANSI B71.4-2004, "American National Standard for Commercial Turf Care Equipment – Safety Specifications" American National Standards Institute, 2004.

[5] ASAE S440.3, "Safety for Powered Lawn and Garden Equipment", American Society of Agricultural and Biological Engineers, St. Joseph, Michigan www.asabe.org, March 2005.

[6] ISO 5395, "Power lawn-mowers, lawn tractors, lawn and garden tractors, professional mowers, and lawn and garden tractors with mowing attachments -- Definitions, safety requirements and test procedures", International Organization for Standardization, Geneva, Switzerland, 1990.

[7] ASTM C1055-03, "Standard Guide for Heated System Surface Conditions That Produce Contact Burn Injuries", ASTM International, 2003.

[8] U.S. Code of Federal Regulations, Title 16, Part 1205.

[9] Docket EPA-HQ-OAR-2004-0008-0321.

[10] Docket EPA-HQ-OAR-2004-0008-0322.

[11] Docket EPA-HQ-OAR-2004-0008-0323.

[12] Docket EPA-HQ-OAR-2004-0008-0332.

[13] Docket EPA-HQ-OAR-2004-0008-0329.

[14] Docket EPA-HQ-OAR-2004-0008-0320.

[15] Docket EPA-HQ-OAR-2004-0008-0327.

[16] U.S. Consumer Product Safety Commission, National Electronic Injury Surveillance System database, 2000-2004.

[17] The Injury/Potential Injury Incident File (IPII) can be found at Docket EPA-HQ-OAR-2004-0008-0325. The In-Depth Investigation (INDP) files can be found at Docket EPA-HQ-OAR-2004-0008-0326.

[18] "NFIRS Data on Gasoline-Fueled Lawn Mowing Equipment, 2002," CPSC memo from Risana Chowdhury to Susan Bathalon, December 7, 2005, Docket EPA-HQ-OAR-2004-0008-0324.

[19] U.S. Consumer Product Safety Commission, "Recalls and Product Safety News", http://www.cpsc.gov/cpscpub/prerel/prerel.html

4. Scenarios for Evaluation of NHH Engines and Equipment

A. SUMMARY OF OTHER INFORMATION CONSIDERED

In this chapter, EPA identifies the key scenarios used in evaluating the incremental impact on safety associated with advanced emission control technology for NHH engines and equipment. The scenarios cover a comprehensive variety of in-use conditions or circumstances which potentially could lead to an increase in burns or fires. These may occur presently or not at all, but are included because of the potential impact on safety if they were to occur. EPA is not identifying these as conditions that will in fact occur, but more as potential or hypothetical conditions should be evaluated. The focus of the analysis is therefore on the incremental impact on the likelihood or that the severity of these scenarios and the potential causes occurring from using more advanced emissions control technology.

In addition to using the CPSC reports and databases, EPA considered additional inputs in identifying the scenarios for evaluation. These included the following:

- OPEI briefing to EPA entitled: "Discussion of Off-Nominal Operating Conditions for Catalyzed Small Off-Road SI Engines and Lawn/Garden Equipment," Oct 26, 2005.[1]

OPEI identified nominal and off nominal conditions and laid out concerns which occur in the lab versus in the field. According to OPEI, off nominal conditions are defined as unintentional and unavoidable conditions during equipment operation which are non-trivial infrequency and may be high consequence events leading to significant increase in fire and heat-related safety hazards. The four general categories of off nominal conditions identified by OPEI include:

i. An increase in the amount of air present in the muffler/catalyst region

ii. Air/Fuel ratio changes affecting catalyst conversion efficiency

iii. Increase of unburned fuel into muffler/catalyst or on hot surfaces of the equipment

iv. Changes in the cooling air flow management system

- National Association of State Fire Marshals memorandum from Margaret Simonson to James Burns, "Recommendations for Independent Research Project on Fire Safety of Measures being Considered to Reduce Emissions of Small Engines in Outdoor Power Equipment," September 22, 2004.[2]

- Memorandum, from Charles Burnham Applied Safety and Ergonomics to Margaret Simonson, National Association of State Fire Marshals entitled, "Request for Data: Air Quality Measures for Small Engines Used with Outdoor Power Equipment," June 18, 2004.[3]

- Letter from William Guerry, Collier, Shannon, Scott, to Jackie Lourenco entitled Re: "CARB's Catalyst Durability Study." September 10, 2002.[4]

- "Lawn-Mower Related Burns," Journal of Burn Care and Rehabilitation, Volume 21, No.8, pp. 403-405.[5]

- "Literature Survey on Garden Machinery (lawnmowers)" prepared by Dutch Consumer and Safety foundation for the Inspectorate for Health Protection and Veterinary Public Health, November 3, 2002.[6]

- Discussion with the National Institute for Standards and Testing (NIST), December 6, 2005.[7]

- "Durability of Low Emissions Small Off-Road Engines," Southwest Research institute, April, 2004.[8]

- Information from meetings, workshops, and discussions with engine and equipment manufacturers including but not limited to:
    - OPEI Presentation to US EPA, May 23, 2005.[9]
    - Public Consultation Meeting, The International Consortium for Fire Safety, Health, and Environment and US EPA, Briggs and Stratton Corporation, October 5, 2005.[10]

In addition to these references, EPA has gained valuable empirical experience in the field testing conducted over the past two years. This testing has increased our understanding of potential failure modes and added to the scope and depth of our planned assessment.

B. SAFETY SCENARIOS FOR EVALUATION

There are a number of ways in which the scenarios of concern could be identified for evaluation and discussion. EPA elected an approach which closely mirrors the problems identified in the CPSC data, while including the other concerns identified in the other sources described in A. above. This provides a comprehensive and methodical approach to analysis and discussion which is provided in the chapters which follow.

Scenario 1: Contact burns

Scenario Description: Thermal burns due to inadvertent contact with hot surface on engine or equipment.

Potential Causes:

a. muffler surface temperature increases due to debris inhibiting flow of cooling air

b. higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine

c. muffler temperature increase due to air-to-fuel ratio enleanment caused by calibration drift over time, fuel system problems or air filter element mal-maintenance

d. exhaust gas leaks increase surface temperatures

e. misfueling: use of highly oxygenated fuel such as E85 (mixture of 85% ethanol and 15% gasoline)

Scenario 2: Debris fire:

Scenario Description: Grass and leaf debris fires on engine/equipment.

Potential Causes:

a. muffler temperature increases due to debris inhibiting flow of cooling air, debris trapped in tight areas blocks air flow, dries out and heats up

b. higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine or exhaust system leaks

c. muffler temperature increase due to A/F ratio enleanment caused by calibration drift over time, air filter element mal-maintenance, or exhaust system leaks

d. exhaust gas leaks increase surface temperatures

e. misfueling: use of highly oxygenated fuel such as E85

Scenario 3: Fires due to fuel leak

Scenario Description: Fires due to fuel leaks on hot surfaces.

Potential Causes:

a. faulty fuel tank

b. faulty fuel line or connection

c. tip-over during maintenance

d. tip over in operation

e. faulty carburetor

f. heat affects fuel tank or fuel line integrity

Scenario 4: Fires related to refueling

Scenario Description: Fires related to spilled fuel or refueling vapor.

Potential Causes:

a. fuel spilled on hot surfaces

b. spilled fuel evaporates or refueling vapors lead to fire indoors

Scenario 5: Fire related to storage and shutdown

Scenario Description: Equipment or structure fire when equipment left unattended after use.

Potential Causes:

a. ignition of nearby easily combustible materials

b. ignition of fuel vapor by an appliance pilot light (or similar open source of ignition)

c. ignition of dry debris on deck

d. ignition of dry debris in field

e. ignition of tarp or other cover over equipment

Scenario 6: Ignition misfire

Scenario Description: Engine malfunction which results in an ignitable mixture of unburnt fuel and air in the muffler.

Potential Causes:

a. misfire caused by partial failure in ignition system (single cylinder engines)

b. misfire caused by failure in ignition system, particularly complete failure of ignition for one cylinder (2 cylinder V-twin engines)

c. after-fire/backfire caused by engine run-on after ignition shut-down due to failure of the engine flywheel brake or carburetor fuel-cut solenoid

Scenario 7: Fire due to rich operation

Scenario Description: Fire due to operation with richer than designed A/F ratio in engine or catalyst.

Potential Causes:

a. fuel system degradation such as faulty carburetor, oil consumption or carburetor deposits

b. faulty or misapplied choke

c. air filter element mal-maintenance

d. debris blocks catalyst venturi

In addition, through the FMEAs, we assess the hazard patterns identified in Chapter 3 related to equipment fire and explosion for an unspecified reason.

Chapter 3 laid out the basic NHH technology, discussed the current safety standards affecting design, and analyzed in-use safety experience. This chapter identifies the key scenarios to evaluate and the causal factors to consider in this assessment. We turn now to a description of the test methods used in the EPA laboratory and field work for NHH engines.

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[1] Docket EPA-HQ-OAR-2004-0008-0310.
[2] Docket EPA-HQ-OAR-2004-0008-0311.
[3] Docket EPA-HQ-OAR-2004-0008-0312.
[4] Docket EPA-HQ-OAR-2004-0008-0313.
[5] Docket EPA-HQ-OAR-2004-0008-0314.
[6] Docket EPA-HQ-OAR-2004-0008-0315.
[7] Docket EPA-HQ-OAR-2004-0008-0316.
[8] Docket EPA-HQ-OAR-2004-0008-0317.
[9] Docket EPA-HQ-OAR-2004-0008-0318.
[10] Docket EPA-HQ-OAR-2004-0008-0319.

5. NHH Test Program

This chapter describes EPA's laboratory and field testing of Class I and Class II engines and equipment. We describe the engines selected for testing, the engine's emissions control systems, and the test methodology used to assess safety of prototype Phase 3 engines compared to current Phase 2 product.

A. ENGINE SELECTION

We selected a total of nineteen nonhandheld SI engines for laboratory and field testing in this study. Twelve of the engines were Class I engines and were evenly split between side-valve and OHV engine designs from four different engine families. Eight of the engines were Class II engines, all OHV engine designs from three different engine families. General specifications for the Class I and Class II engines that were tested are provided in Tables 5-1 and 5-2. The engines were obtained by purchasing residential lawn mowers and lawn tractors from retail stores in SE Michigan.

The two Class I side-valve engine families selected were certified to U.S. Federal Phase 2 Emission Standards, without the use of emissions credit, as well as California Air Resources Board (CARB) Tier 2 Emission Standards. Together these two engine families represented approximately 50% of all gasoline-SI Class I side-valve engine sales, and they also represented 75% of gasoline-SI Class I side-valve engines certified to Phase 2 for the 2004 model year.

The two Class I OHV engine families selected for testing were also certified to the Phase 2 emission standards. Together these two engine families represented approximately 46% of all gasoline-SI Class I OHV engine sales, and approximately 50% of Class I, OHV engines certified to Phase 2 for the 2004 model year.

Table 5-1: Summary of Class I engine and equipment specifications. All of the engines tested were from residential walk-behind lawn mower applications.

Engine ID numbers (grouped by engine family)	243, 244, 245	241, 255	258	236, 246, 248, 249, 259
Emissions Standard (as determined from "emissions tag")	Federal Phase 2, CARB Tier 2	Federal Phase 2, CARB Tier 2	Federal Phase 2, CARB Tier 2	Federal Phase 2, CARB Tier 2
Advertised Power (h.p.)	5.5	6.75	6.0	6.0
Maximum Brake Power (b.h.p)	3.2-3.7	4.3 - 4.5	3.0	2.9 - 3.0
Governed Speed @ 75%-10% of maximum brake torque (rpm)	2700 – 2900	2800 – 3100	3160 – 3260	2700-2900
Engine Displacement (liters)	0.16	0.19	0.19	0.20
Valve Arrangement	OHV	OHV	Side-valve	Side-valve
Equipment Used for Field Testing	Self-propelled walk-behind lawn mower, configured for mulching	Not field tested – obtained from self-propelled walk-behind lawn mowers	Not field tested – obtained from a self-propelled walk-behind lawn mower	Self-propelled walk-behind lawn mower, configured for mulching

Two of the three Class II engine families selected for testing were both OHV designs, and together represent approximately 24% of the gasoline-SI Class II Phase 2 engine sales for the 2004 model year. The third engine family (engines 254 and 256) is a new design that has superseded one of the other Class II engine families tested (engines 232 and 233) in high-volume consumer lawn and garden applications.

Table 5-2: Summary of Class II engine specifications. All of the engines tested were from residential lawn tractor applications.

Engine ID numbers (grouped by engine family)	231, 251, 252, 253	232, 233	254, 256
Emissions Standard (transcribed from "emissions tag")	Federal Phase 2, CARB Tier 2	Federal Phase 2, CARB Tier 2	Federal Phase 2, CARB Tier 2
Advertised Power (h.p.)	18.0	17.5	20
Maximum Brake Power (b.h.p) @ 3060 rpm	12.8	12.4	11.8
Governed Speed (rpm) @ 75%-10% of maximum brake torque	2900 – 3100	2900 – 3150	3150-3350
Engine Displacement (liters)	0.5	0.49	0.6
Valve Arrangement	OHV	OHV	OHV
Equipment Used for Field Testing	Residential lawn tractor w/manual transmission	Residential lawn tractor w/manual transmission	Residential lawn tractor w/hydrostatic drive

B. ENGINE MODIFICATIONS

This section describes the advanced emission control systems developed for the engines in section A. Note that brief descriptions of tested configurations are also included within the tabulated emissions results in Appendix B.

Class I – 10 g/kW-hr systems

EPA conducted a literature search of existing catalyst-muffler designs for Class I engines. Three basic designs covered under four separate patents showed promise for application to Class I Phase 2 engines.1,2,3,4 These designs share a number of common features, including:

- Compact design, being virtually the same size as some standard mufflers available for this engine
- Use of a passive exhaust venturi or exhaust ejector for introduction of secondary air
- Exhaust pulse dampening located upstream of the venturi
- Relatively small substrate volume

One of the catalyst-muffler designs[1] was already in mass production by an OEM for use on European walk-behind lawn mowers (Figure 5-1). EPA purchased several of these units and conducted a preliminary engineering and chemical analysis. This particular design used a simple, stamped venturi for passive secondary air entrainment and a small (approximately 20 cc or 1.2 in3) cordierite monolith with 400 cell/square-inch (cpsi) construction common in automotive applications. The catalyst substrate was retained with a common automotive-type matting material. PGM loading was approximately 30 g/ft3 with a Pt:Pd:Rh ratio of approximately 5:0:1.

Following initial analysis of the OEM European catalyst-muffler, it was determined that an increase in catalyst volume might be needed to provide sub-10 g/kW-hr HC+NOx emissions at high hours after taking into consideration an expected degree of catalyst oil poisoning and degradation of engine-out emissions. Initial prototype samples were fabricated by lengthening the muffler by 20 mm and doubling the substrate volume within the production European catalyst-muffler (Figure 5-2). Although increasing substrate volume in this manner increases exhaust backpressure, for the engine family that this catalyst muffler was tested with there was virtually identical peak power output at wide-open-throttle (WOT) at the A-Cycle test speed (3060 rpm) for both the modified catalyst-muffler and the OEM muffler. Similar results were achieved with other catalyst muffler configurations that tested with other engines. Thus the backpressure increase that resulted from the use of catalysts within the exhaust systems was not sufficient to impact power output. This may have been in part due to the relatively small catalyst volumes tested, the geometry of the substrates (generally much lower cell density than automotive substrates, and also generally "shorter-fatter" geometries), and the exhaust restriction of the substrates relative to that of other parts of the exhaust system.

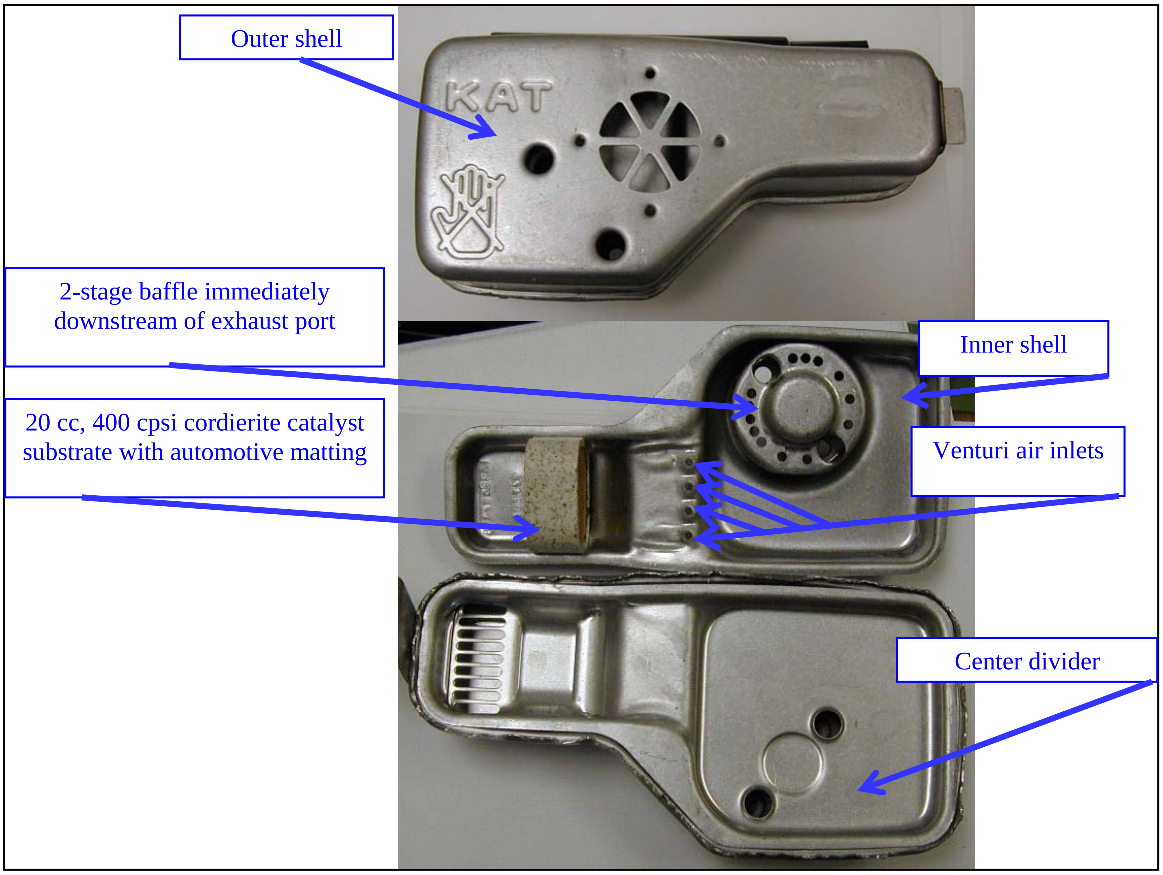
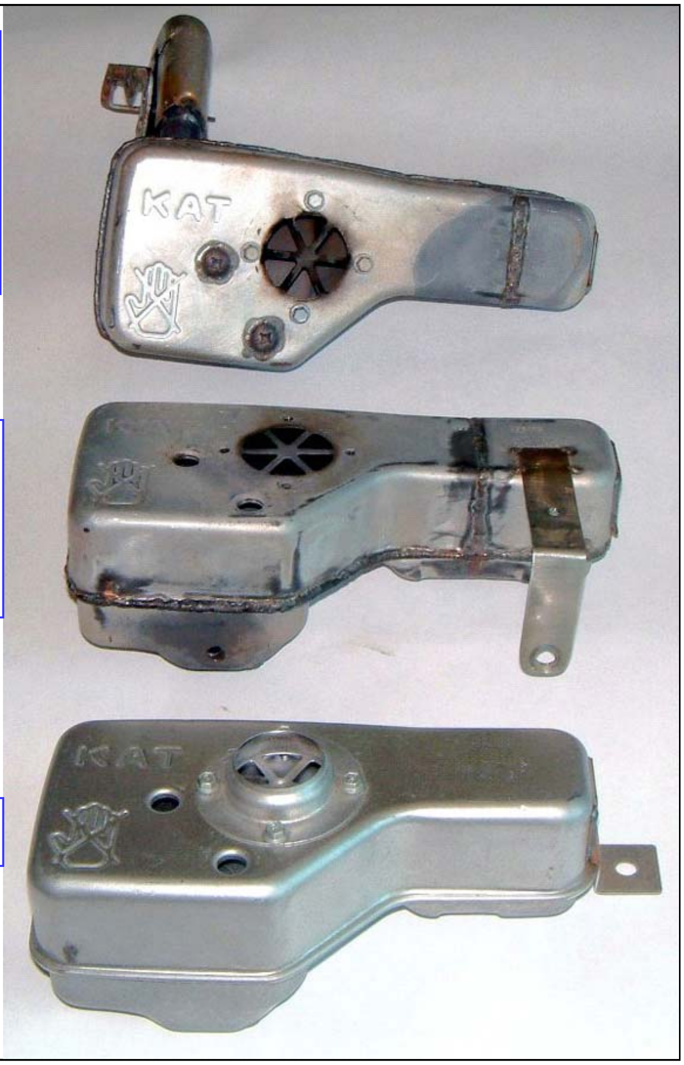


Figure 5-1: Details of an OEM catalyst-muffler from a European walk-behind lawn mower application.



Catalyst-muffler reconfigured with a second 20 cc substrate (40 cc total), repositioned inlet and modified internal baffles. This is the unit tested with engine 241.

Catalyst-muffler reconfigured with a second 20 cc substrate (40 cc total). This is similar to the configuration tested with engine 258.

OEM European Catalyst-muffler

Figure 5-2: Catalyst-muffler from Figure 5-1 (bottom) modified with additional catalyst volume (center) and with modifications to the inlet and internal baffles to allow use with engine 241 (top).

The lengthened European catalyst-muffler was further modified by changing the exhaust inlet to allow its use on an additional engine type (see Figure 5-2). Additional catalysts with different formulation and construction were obtained from major North American catalyst suppliers (Figure 5-3). Catalyst substrates tested included:

1. 34 cc, 100 cpsi metal monoliths;
2. 44 cc, 200 cpsi metal monoliths;
3. metal-mesh substrates;
4. 22 cc 200 cpsi metal monolith with a 20 mm dia. X 73 mm long tubular pre-catalyst[c]; and
5. the aforementioned 400 cpsi cordierite monoliths, doubled to provide approximately 40 cc catalyst volume (Figure 5-2).

Ceramic monoliths have been used successfully in OEM applications in Europe, and have proven durable provide appropriate matting and support for the substrate is provided within the catalyst muffler design. Metal monoliths are more resistant to shock than ceramic monoliths, and may be easier to package into catalyst mufflers for some applications, but are generally more expensive. Metal mesh substrates approach the cost of ceramic monoliths, and have acceptable durability due to recent improvements in substrate packaging and washcoat adhesion. All three substrate types were tested because they represent the range of types that EPA expects to be used to comply with the California Tier 3 and the expected Federal Phase 3 standards for different applications.

Most of the prototype catalyst-mufflers contained catalyst substrates with different construction and PGM loading in the OEM European catalyst-muffler housing. Some designs also incorporated additional heat-shielding or shrouding (see Figure 5-4). One prototype catalyst-muffler, tested with engine 243, was completely fabricated from scratch using a tubular venturi and a general layout similar to previous designs (Figure 5-5).3,[4] An additional catalyst-muffler for engine 249 was tested without the use of secondary air and was fit entirely within the standard OEM muffler.

The tubular pre-catalysts were installed upstream of the secondary-air-venturi, with a 22 cc 200 cpsi monolith installed downstream of the venturi (Engines 243 and 255). The catalyst-muffler tested with engine 255 is shown in Figure 5-6.

The PGM loadings on the monolithic substrates ranged from 30 g/ft3 to 50 g/ft3. Generally, higher loadings were used with smaller substrate volumes to provide a similar overall level of PGM surface area within a smaller packaging volume. The loading ratio of 5:0:1 (Pt:Pd:Rh) as used with the production catalyst-muffler was the most common, but loading ratios ranging from 4:0:1 to 0.33:3.66:1 and one Rh-only only were also tested. The specific loading of any particular catalyst tested and its relationship to particular data results was considered proprietary, but general trends in emissions versus PGM loading and loading ratio will be discussed within the results section.

When selecting catalyst secondary air configurations to test with each engine, the primary design target was to achieve less than 10 g/kW-hr HC+NOx emissions at the 125 hour useful life level because this is the most common for residential walk-behind lawn mowers. A maximum of 7.0 g/kW-hr HC+NOx target was set for low-hour emissions performance for the Class I residential lawn mower engines to allow for engine and catalyst degradation over the 125-hour useful life requirements for these engines. Secondary design targets included minimization of CO oxidation at moderate to high load conditions (e.g., A-cycle modes 1 and 2) and exhaust system surface temperatures comparable to those of current Phase 2 OEM systems.

The OEM versions of engines 243, 244 and 245 were equipped with mufflers enclosed in shrouds that directed air flow across the surface of the mufflers for additional cooling of the exhaust system. The catalyst-muffler systems developed for engines 243, 244, and 245 were equipped with shrouds providing a similar function, but with the air-outlet of the shroud relocated in order to provide improved air flow over the outer surface of the catalyst-muffler.

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[c] A tube with a single, perforated channel in which all of the internal surfaces are washcoated.

These engines also were equipped with an exhaust ejector over the exhaust outlet of the catalyst-mufflers to both cool the exiting exhaust gases and to provide for additional heat rejection from the surface of the shroud. A similar shroud and ejector system was tested with engine 249.

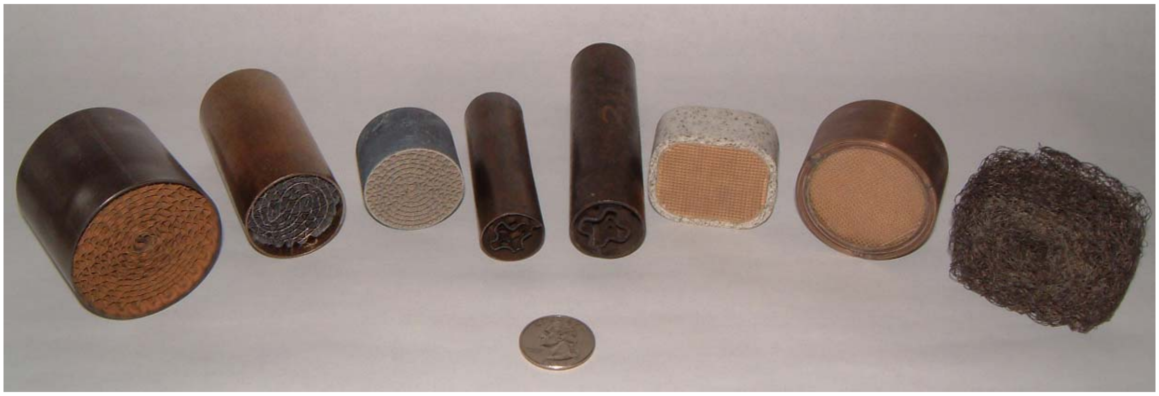

Figure 5-3: Some of the catalyst substrate types evaluated by EPA with Class I and Class II engines included (from left to right) 100 cpsi metal monoliths (in 50 mm and 33 mm diameters); 200 cpsi metal monolith; catalyzed tube pre-catalysts (in 20 mm and 25 mm diameters); 400 cpsi coridierite (square-oval and round) and metal-mesh. The 50 mm diameter catalyst on the far left was used with Class II engine test configurations. The remaining catalysts were tested with Class I engines.

Figure 5-4: Engine 236 with catalyst-muffler installed on dynamometer test stand at the U.S. EPA National Vehicle and Fuel Emissions Laboratory (NVFEL). The muffler was derived from a production European catalyst-muffler. It was modified to allow installation onto a different engine type, and a 44 cc metal monolith catalyst was substituted for the original ceramic monolith. A small heat shield was added to prevent heating of the intake manifold. The catalyst-muffler configurations for engines 246 and 249 were similar, but with different catalyst substrates and PGM loadings.

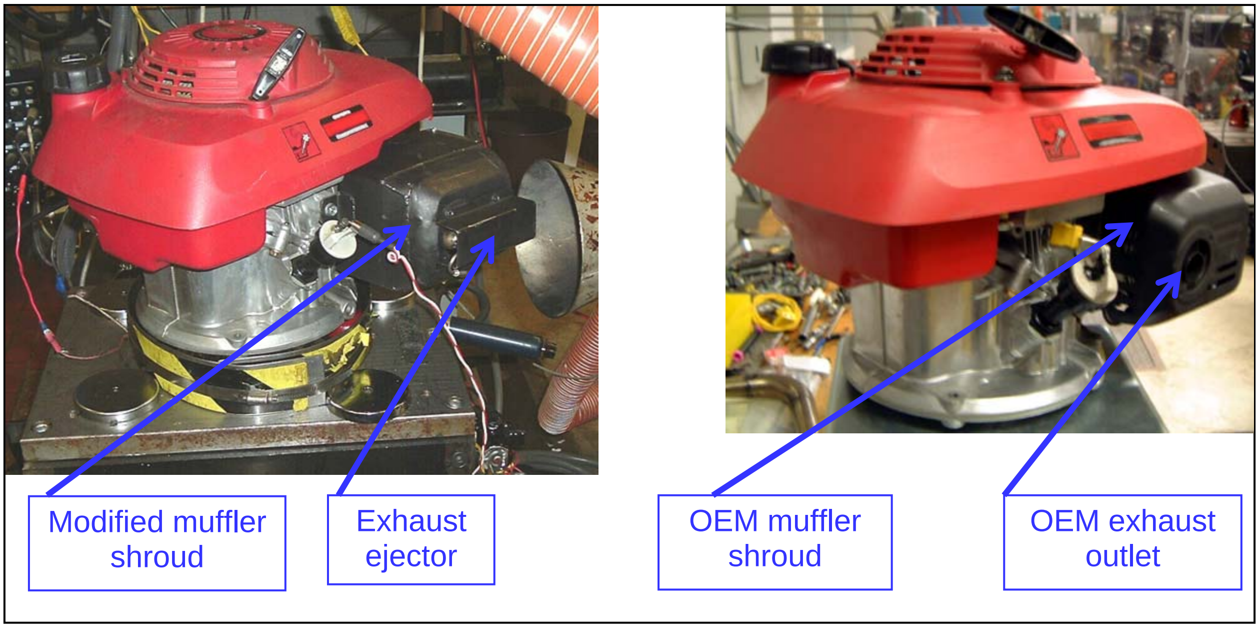

Figure 5-5: Engine 243 (left) equipped with a catalyst-muffler, passive venturi-secondary-air, muffler air shroud and exhaust ejector compared to a similar engine (right) with the OEM muffler and muffler air shroud.

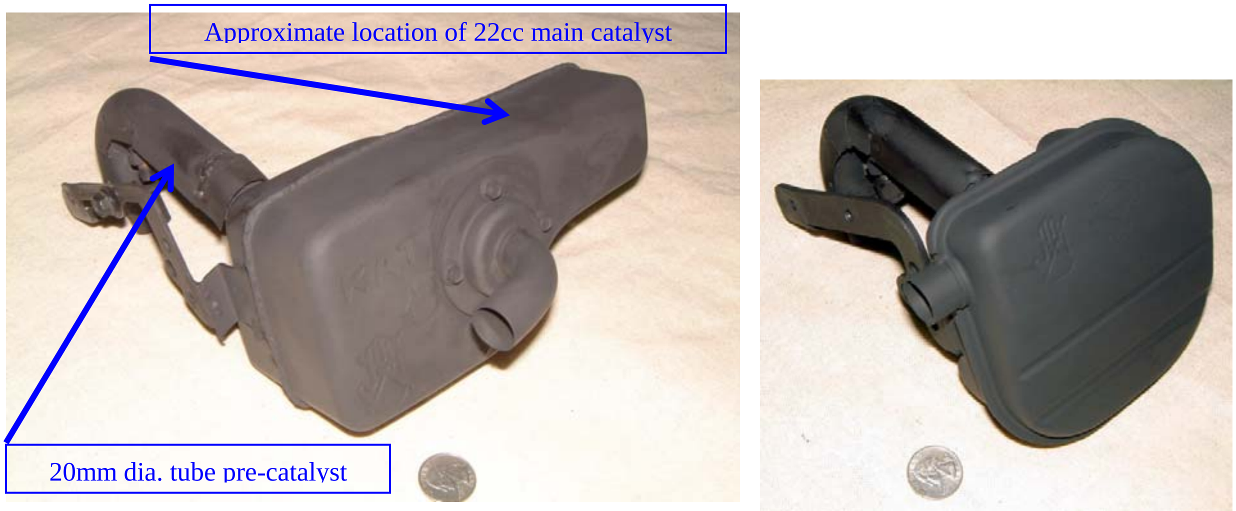

Figure 5-6: Catalyst-muffler (left) and OEM muffler (right) tested with engine 255.

Class II – 3.5 g/kW-hr HC+NOx system

Engines 231 and 232 were fitted with an ECU and components originally developed for the Asian motor-scooters and small-displacement motorcycles. The fueling logic was speed-throttle-based with barometric pressure (BP) and MAP correction capability. The OEM ignition system and mechanical speed governing were maintained.

The fuel system consisted of an electronic fuel pump, external regulator, and small fuel injector. The fuel pump has a flow capacity of 2.5 grams per second at 250 kPa, which was the regulator's pressure setting. The fuel pumps used were also designed with power consumption minimized to 1 amp. Engine 231 used an in-line fuel pump and engine 232 used an in-tank fuel pump. The ECU controlled the fuel pump with a pulse-width-modulated low side drive. The injectors used were a two-hole design with 12 Degree spray cone, and has a static flow of 1.4 grams per second at the 250 kPa regulated fuel pressure.

The sensors for the ECU were minimized to a throttle position sensor (TPS), air charge temperature sensor, oil temperature sensor, ECU board-mounted MAP sensor, and crankshaft variable reluctance sensor for a two-tooth crankshaft target. The throttle position sensor (TPS) required a zero-return spring force to avoid interference with operation of the engine's mechanical governor. Initially a springless linear potentiometer mounted on the governor linkage primary control arm was used for TPS. As development progressed, this unit was replaced with a TPS sensor from an automotive electronic throttle control module.

Catalyst formulations and the air-to-fuel ratio calibration of the open-loop electronic fuel injection (EFI) system were selected in a manner that prioritized NOx reduction and HC oxidation over CO oxidation. The catalyst-mufflers were selected for further testing by first screening six different catalysts with varying washcoating formulations, substrate volume and substrate construction. Specific PGM loadings, loading ratios, and catalyst construction for the catalysts used in this study were proprietary, but in general loadings were between 50 and 70 g/ft3, and loading ratios varied from 0:5:1 to 5:0:1. Both 200 cpsi and 400 cpsi metal-foil monolithic catalyst substrates were tested. Catalyst volume varied from approximately 50% to 55% of the engine displacement. A typical catalyst-muffler is shown in Figure 5-7.

Details of the installation of modified components as installed on a lawn tractor chassis are shown in Figure 5-8. The engine air shrouding was extended and the routing of cooling air through the chassis of the lawn tractors was changed to route the cooling air from the engine fan, downstream of the engine, over the catalyst-muffler and exiting either to the side or the front of the lawn tractor. The resulting forced air cooling reduced exhaust system temperatures and also prevented debris build-up in the areas adjacent to the exhaust system components.

Figure 5-7: The photos on the left show the layout of the 3-chamber OEM Nelson lawn tractor muffler. The mufflers used with the other Class II lawn tractor engines were very similar except for the inlet-pipe configuration. OEM mufflers were sectioned and a catalyst monolith was installed between the upper and lower chambers. The outlet was relocated to facilitate use with an exhaust ejector, and the inlet was flanged to allow use of the catalyst-muffler in different chassis configurations and to provide the additional clearance necessary for testing the catalyst-muffler while the engine was installed on the dynamometer. The catalyst mufflers for the 8.0 g/kW-hr configurations fit entirely within the OEM muffler (upper right and center right). The catalyst-mufflers fabricated for the 3.5 g/kW-hr configurations (example, lower right) had a cylindrical section that extended above the main body of the muffler to allow space for additional catalyst volume, and the third chamber was relocated to the top half of the muffler. Use of an oval monolith would have allowed packaging within the OEM muffler space, but an appropriate-size oval monolith was not available at the time of testing.

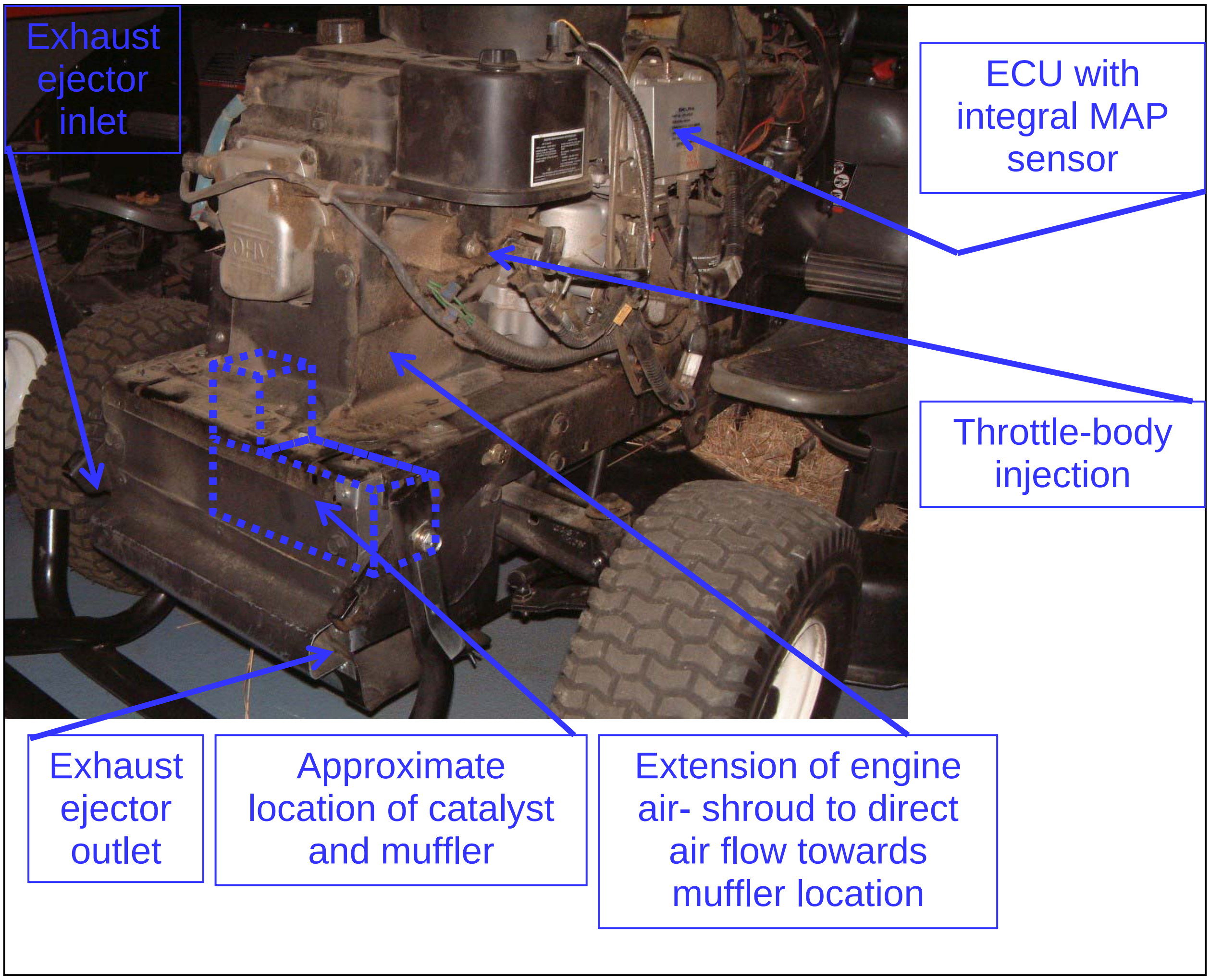

Figure 5-8: Engine 232 installed in a lawn tractor chassis, showing details of the engine and chassis modifications. The exhaust ejector extends for nearly the entire width of the cavity in which the muffler is housed.

Class II – 8.0 g/kW-hr HC+NOx systems

The tested configurations of engines 253 and 254 used OEM carburetors and air-to-fuel ratio calibration. No changes were made to the base Phase 2 configuration of the engine other than those necessary to install the catalyst-mufflers. Four different catalysts were initially tested with varying PGM loading, loading ratio, substrate volume and substrate construction, and two were selected for operation in the field. Specific PGM loadings, loading ratios, and catalyst construction for the catalysts used in this study were proprietary, but in general loadings were between 30 and 40 g/ft3, loading ratios were approximately 5:0:1, and both 200 cpsi metal-foil and 400 cpsi ceramic monolithic catalyst substrates were tested. Availability of appropriately sized and coated substrates had more impact on choice of substrate material since performance was comparable between the two substrate types at this level of emissions control. The catalyst volumes varied from approximately 25% to 40% of the engine displacement. Photographs of the catalyst-muffler configurations for engines 253 and 254 are shown in Figures 5-9 and 5-10.

Figure 5-9: Engine 253 undergoing dynamometer testing with catalyst-muffler installed. The addition of a single 250cc 400 cpsi ceramic monolith into the OEM muffler and minor physical modifications to the exhaust-muffler were the only changes made to this Class II, Phase 2 engine. The exhaust-lambda sensor mounted into the exhaust pipe was used for laboratory measurement purposes only.

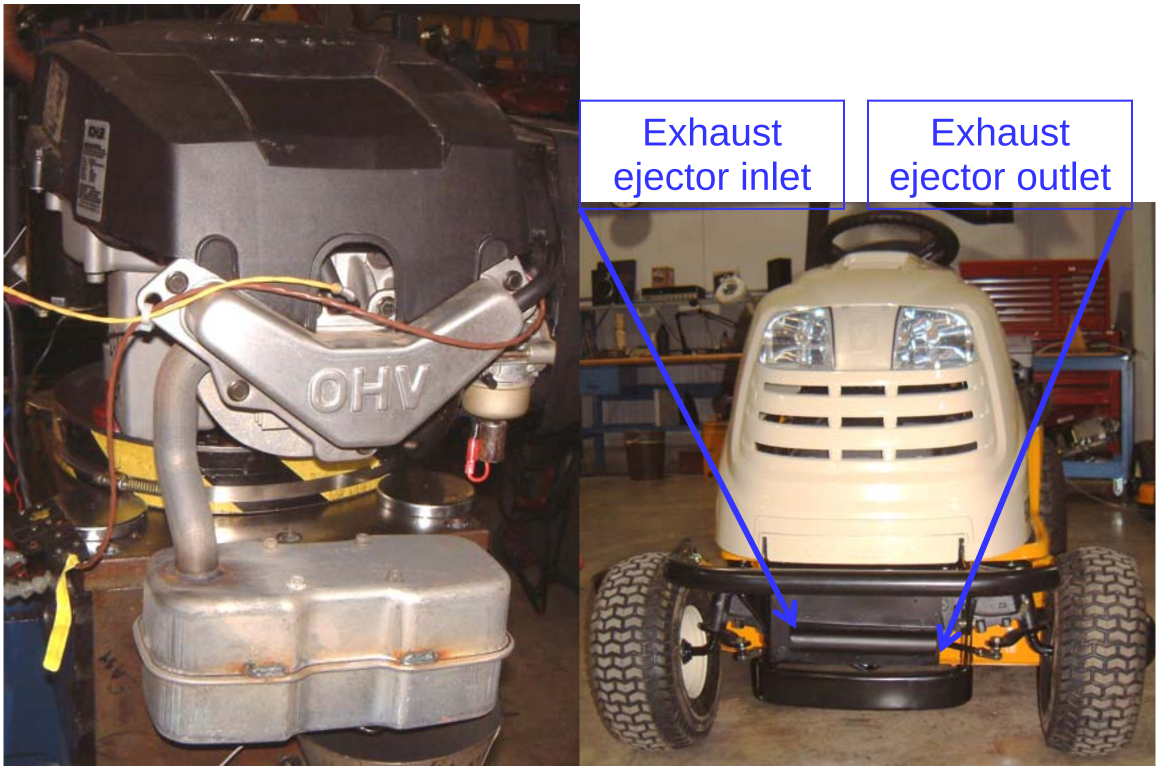

Figure 5-10: Engine 254 undergoing dynamometer testing with catalyst-muffler installed (left) and installed in a lawn tractor chassis (right). The addition of two 79cc, 100 cpsi metal-monolith catalysts into the OEM muffler and minor modifications of the exhaust-muffler were the only changes made to this Class II, Phase 2 engine.

C. INFRARED THERMAL IMAGING

The primary experimental method used for comparison of exhaust system, engine, and equipment surface temperatures during laboratory and field testing was via infrared (IR) thermal imaging.5,6,7 IR thermal imaging is based on principles originally developed for target finding and surveillance by the U.S. Department of Defense. IR still images in the laboratory were obtained using an "IR Snapshot" IR imager. Full motion IR imaging in the laboratory and in the field was obtained using an "IR Flexcam T" infrared imager. Both IR imagers correct the IR radiance from any single point on the target surface in a manner that a captures precise, accurate representation of the true temperature at that location. The following assumptions are necessary to allow this sort of analysis:

1. The IR absorption of the air path between the target and the instrument is negligible, and
2. No IR energy is transmitted through the target from sources behind the target.

In order to correct for reflection of the ambient background, it was necessary for the operator of the imager to input the background temperature. This was monitored in the laboratory and in the field using J-type thermocouples. It should be noted that during laboratory testing EPA-NVFEL test cells are held at a nearly constant background temperature of 25 °C ± 1 °C.

The operator of the imager also provided inputs for the targets estimated emissivity. All the primary temperature targets (Mufflers/Catalysts) were painted with a high temperature flat-black paint with a dull matte finish. This was used to even out the emissivity over the surface of the object as well as to increase the value of the emissivity of the object. An emissivity of 0.9 was used for this project. To check the validity of the emissivity assumptions, a comparison of the surface temperature measured with the IR imager was made to a known surface temperature measured with a J-type thermocouple. The temperatures were within 1% of agreement.

The IR imagers have the following general specifications:

- They use microbolometer detectors that require no cryogenic cooling.
- The detector elements are square and are located in a rectangular grid.
- The optical path of the camera includes an appropriate band-pass filter for the temperature range of interest.
- The IR Snapshot Camera has a NIST traceable calibration from 10 °C to 1200 °C with accuracy of 2 °C or 2% of reading.
- The IR FlexCam has a NIST traceable calibration from 0 °C to 600 °C with accuracy of 2 °C or 2% of reading.
- The lenses for both cameras are made from germanium and are anti-reflective coated for high transmission in the temperature range of choice.

Both imagers were calibrated using NIST traceable temperature standards prior to the beginning of the IR thermal imaging tests and at the end of the test program. No change to the calibration curve of either instrument was necessary between the first and second set of calibrations. Calibration results are provided in Appendix A.

D. LABORATORY TEST PROCEDURES

Operation over the Federal A-Cycle

U.S. Federal Phase 2 A-cycle test (table 5-3) was used to gather emissions data and to provide a broad range of engine operational conditions under which exhaust system surface temperatures could be measured using the infrared thermal imaging equipment.8 The engine dynamometer test cell was kept a temperature of 25 °C ± 1 °C, with an absolute humidity of 75 grains-H2O/lbm-dry-air. Tests were conducted using a 20 kW (maximum) Edy-current dynamometer.

IR still images were used during laboratory testing to allow more precise determination of peak temperatures and to allow further flexibility within the temperature analyses than was possible with the full-motion-video IR imaging.

Some of the engines tested were equipped with a user-selectable governor speed setting. For these engines the speed setting was kept in the 100% position for A-cycle modes 2, 3, 4, and 5. The user-selectable governor speed setting was set to 0% (low-speed idle) for mode 6.

Some of the engines had no provision for user adjustment of the governor speed. For these engines, engine operation occurred with the engine governor controlling engine speed for modes 2, 3, 4, 5 and 6 with no modifications or adjustments to engine governor operation. Mode 6 was run as a high-speed-idle condition.

In all cases, mode 1 of the A-cycle was obtained via bypassing the governor and operating the engine with a fixed wide-open-throttle (WOT) and the dynamometer control set to the A-speed (3060 rpm). Torque control provided a coefficient of variance of 1 % or less in measured torque at WOT.

At each of the 6 steady-state modes of the A-cycle test, IR images were acquired following stabilization of cylinder head temperature to a value of approximately:

$$\Delta T/\Delta t < 1\ ^\circ\text{C/minute}$$

where ΔT is the change in temperature measured with a K-type thermocouple embedded within a sparkplug gasked for cylinder head temperature measurement, and Δt is the measured time interval. Depending on the engine tested, stabilization required between five and ten minutes in A-cycle Mode 1 and approximately five to six minutes for Modes 2 through 6.

Table 5-3: EPA A-Cycle Intermediate Speed Steady-State Engine Dynamometer Test

EPA A-cycle Mode	1	2	3	4	5	6
Engine Speed (rpm)	3060	100% governed	100% governed	100% governed	100% governed	0% governed (low idle)
Torque	100% (@ WOT)	75%	50%	25%	10%	0
Cycle Weighting Factor	9%	20%	29%	30%	7%	5%

Notes:
The engine speed governor was disabled for Mode 1, and the engine was operated at WOT with the dynamometer in speed-control mode set to 3060 rpm. Modes 2-5 were operated with the engine speed governor set to its 100% position and with the dynamometer in torque-control mode, with percent torque based on the average Mode 1 value. Mode 6 was a no-load, low idle test point for both Class II engines, and for engines 243, 244, and 245. Mode 6 was a no-load, high-idle test point for the remaining engines since these were not equipped with a user-selectable speed setting for the engine governor.

The limiting factor in the uncertainty of the IR surface temperature measurements was the accuracy (± 2% of point) of the thermal imagers rather than test to test variability, thus single tests were conducted for each tested configurations. Catalyst-muffler and OEM muffler configurations for each engine were conducted within one test day.

Hot Soak Testing

Part way through the test program, EPA began conducting hot soak tests to compare the rate of cooling of catalyst-muffler equipped engines to that of engines equipped with OEM mufflers. Hot soaks are timed measurements which are made following the engine shut-down after sustained operation. Laboratory hot soak tests were conducted following sustained, temperature stabilized operation at 100% load at WOT conditions (A-cycle Mode 1) and following sustained, temperature stabilized operation at 50% load (A-cycle Mode 3). Hot soak tests were also conducted in the field following sustained grass cutting operations (see the section on "Field Operation" in this chapter). The 100% load point represented a worst case test with the highest obtainable exhaust system surface temperatures. The tested engines were equipped with engine speed governors that could only sustain WOT momentarily during normal operation. The 50% load point was more representative of temperatures achieved during moderate to heavy grass cutting conditions, and resulted in comparable surface temperatures to temperatures measured during field testing. For either the 100% or 50% load operational point, the engine was operated until stable cylinder head and oil temperature conditions were achieved. Stabilization required approximately six to eight minutes of operation for the WOT condition and approximately five to six minutes for the 50% load condition, depending on the engine. The ignition to the engine was then turned off and a timer was started. Infrared thermal "still" images were taken initially at 30 and 60 seconds following engine shut-down and at 1-minute intervals thereafter. Manufacturer's recommendations within equipment owner's manuals for equipment using engine-mounted fuel tanks (e.g., walk-behind lawn mowers) typically recommended waiting 2-minutes after engine shut-down before opening the cap of the fuel tank. Thus peak surface temperatures 2-minutes after engine shut-down were compared to the auto-ignition temperature of regular-grade gasoline (approximately 250 °C), particularly for the hot-soak tests from the 50% load point and for tests of Class I engines that used fuel tanks mounted to the engine. The manufacturer's recommendations for lawn tractor refueling did not stipulate a specific waiting time prior to refueling. The 2-minute period appeared to adequately represent common usage of residential lawn equipment, so this point during the hot soak period was also used for comparison of the Class II engine and lawn tractor configurations.

After-fire Testing

Two engine manufacturers identified after-fire due to engine run-on following a shut-down under high inertial load to be a potential safety issue. After-fire can occur when an engine is turning a high inertial load (e.g., a generator). If the ignition is turned off, and there is no means to physically stop engine rotation, then the inertial load will temporarily keep the engine spinning. The mechanical governor will pull the carburetor throttle wide open, which will both reduce engine braking and can allow a full air-fuel charge to enter the engine. Because the ignition is shut off, the full air-fuel charge exits the exhaust valve and enters the muffler. The air-fuel charge can ignite on hot surfaces and an "after-fire" flame can propagate through the muffler and exit the muffler or tailpipe. Proper engineering design typically prevents run-on after-fire from occurring. Most Class I and Class II engines used in high-inertia applications are equipped with either

1. a flywheel brake to rapidly stop the engine from spinning (within 3 seconds or less), or

2. a fuel cut solenoid that interrupts fuel flow from the float bowl to the carburetor venturi, thus preventing fuel from flowing into the intake port and out the exhaust port after the ignition is turned off.

Run-on after-fire was encountered with carbureted, catalyst-equipped automobile and light-truck engines in the 1970s and 1980s, particularly with manual transmission vehicles coasting down long grades. One way that the issue was addressed for these applications was to build simple flame arresting properties into the mufflers.9 Flame arresting designs route the exhaust gases through channels, passages and/or perforated metal baffles that are designed to absorb heat from the gases and thus extinguish a flame front. Flame arresting properties can be directly incorporated into the sound attenuating baffles within the muffler.

Engine 241 was used for after-fire testing. The after fire testing replicated conditions of engine run-on due to an inertial load on an engine after the ignition is shut off. Testing occurred at near the end of the regulatory useful life for the engine (125 hours) following dynamometer aging of the engine and catalyst-muffler. This particular engine was tested with a standard OEM "shallow-box" style muffler with a central baffle-plate perpendicular to the muffler inlet that divided the muffler approximately in half, similar to the OEM muffler shown on the right half of Figure 5-6. This engine and OEM muffler was chosen because it had relatively high exhaust port temperatures and because it demonstrated a consistent tendency for after-fire immediately following engine shut-down during WOT hot-soak tests that were conducted. The engine was also tested with a catalyst-muffler with venturi secondary air and 40 cc cordierite monolith catalyst similar to the one pictured at the top of Figure 5-2. Flame arresting properties were incorporated into the two-stage baffle located upstream of the secondary air venturi.

The engine was operated at the 100% load, WOT condition on an Eddy-current dynamometer until stable cylinder head and oil temperature conditions were achieved. The WOT condition was chosen to attain the highest achievable exhaust gas temperatures and exhaust system surface temperatures. The engine's flywheel brake was fixed into a disengaged position. The engine ignition was shut-off and the dynamometer load was simultaneously dropped to zero. The engine continued to spin due to the inertia of the dynamometer for approximately 7 seconds before stopping completely. This allowed air and fuel to be drawn through the engine and into the exhaust system without combustion in the engines combustion chamber. The condition simulated shut-down with a high inertial load and with failure of a fuel-cut solenoid (typically used with generator sets and lawn tractors to prevent after-fire) or failure of a flywheel brake (used with all walk-behind lawn mowers for blade safety and to prevent after-fire). Note that federal regulations require cutting blades of walk-behind mowers to stop within 3-seconds of disengagement of the blade control, and 1- to 2-seconds is typical.10 There is currently no federal requirement regarding blade-stopping time for ride-on lawn equipment. There is an ANSI recommendation of 5 seconds for blade stopping following disengagement of the blade control.11

Digital video of the after-fire tests was acquired to allow direct comparison of the OEM and catalyst-muffler configurations. The test was repeated four times for the OEM muffler configuration. Immediately following the OEM muffler testing, the test was repeated four times using the catalyst muffler.

Misfire Testing

Engine 255 was used for testing under conditions of partial ignition misfire. An optical encoder providing 360 counts per engine revolution (one crank-angle-degree resolution) was installed onto the engine crankshaft output. A laboratory controller temporarily grounded the ignition coil cut-off circuit based on input from the optical encoder and the degree of misfire desired. Initially, encoder data was acquired for 360 counts per revolution at a particular engine operating condition, and a count of up to 1000 engine combustion cycles (2000 engine revolutions) was initiated. When the ignition coil circuit was grounded, a complete 720 crank angle degrees (CAD) (or two complete crankshaft revolutions) of ignition misfire would occur. This alleviated the need to track top dead center (TDC) and spark timing. The series of 1000 cycles could be continuously looped to allow continuous operation at a particular percentage of ignition misfire. Misfire could be made in equal intervals, so two misfires in 1000 cycles could occur at cycles 500 and 1000. Similarly, three misfires could occur following 333, 666, and 999 cycles. Other misfire interval combinations were also evaluated. The cycle count of 1000 was chosen arbitrarily and could be adjusted to other values to check the effect of duration between misfires or to allow a higher rate of misfire resolution. The final configuration used during testing utilized random number generation to randomly select the specific cycles on which misfire would occur, while still allowing selection of the total percentage of misfire events. For example, during prove-out of the misfire generation, the system was configured to cause 3% of the ignition firings to misfire over 100 complete engine cycles and the random number generator provided misfire occurrences at cycles 12, 25, 89.

The next step was to determine a reasonable operating condition (speed and load) for operating the engine under partial misfire. An AC motoring dynamometer was used to map the load provided by the cutting blade during engine operation over a range of typical engine speeds. This essentially provided a torque curve analogous to a "propeller curve" for the conditions under which the cutting blade was spinning but not cutting grass. The cutting blade torque curve generated was thus established as the minimum torque point for engine operation. The engine was operated with engine speed controlled by the engine governor, and misfire was initially induced during operation on the dynamometer along the generated cutting blade torque curve. Operation of the engine beyond 25% ignition misfire resulted in extremely erratic engine operation and vibration and premature failure of the coupling between the engine and the dynamometer. When operated at the 25% misfire condition, the erratic engine operation would be immediately noticeable to the operator, causing engine stumbling, audible misfire and backfire, and greatly reduced ability for the engine pick up load. Sustained operation at 25% misfire was chosen as the operational point for analysis of exhaust system surface temperatures. Even this operational point should be considered a conservative estimate of a maximum misfire level since grass cutting operations and the power-take-off for the wheel drive system would require more engine torque output than the cutting blade torque curve used during testing, which was approximately equivalent to torque of the 25% load A-cycle mode 4 test point at the speed encountered during misfire.

The engine was tested with the OEM muffler and the catalyst-muffler shown in figure 5-6. Following initiation of sustained 25% misfire and stabilization of exhaust gas temperatures measured at the exhaust port, IR thermal images were taken of both the OEM muffler and catalyst-muffler configurations to allow comparison of surface temperatures.

Simulated Rich Operation

Engine 255 was also used for simulated rich operation. A carburetor was modified by changing the main jet to provide an air-to-fuel ratio number approximately 1.0 to 1.5 units richer than the standard carburetor jetting. This air-to-fuel ratio was consistent with test results obtained from a similar engine previously tested by EPA (engine #1514) that returned from field operations running excessively rich. The rich operation was found to be due to a float-valve that was partially contaminated with debris.12 The engine was tested in this condition over all 6 modes of the EPA A-cycle and with both an OEM muffler and with the same catalyst-muffler configuration used for the misfire testing.

E. FIELD OPERATION

Field operation was conducted to:

1. Obtain operational experience with both OEM and catalyst-equipped engine configurations
2. Provide an accelerated means of accumulating engine hours to assess the emissions of both OEM Phase 2 and catalyst-equipped engines at either mid-life or near the end of useful life
3. Provide a means to assess surface temperatures of lawn care equipment during grass cutting operations with the engines installed on equipment chassis

Installation into a chassis was particularly important for the IR thermal imaging analysis of the lawn tractor applications. The chassis included heat shielding and the ejectors used with the catalyst-muffler configurations were installed onto the chassis. Cooling air-flow downstream of the engine was also routed through the chassis and over the catalyst-mufflers to improve heat rejection. These subsystems could not be adequately duplicated on the engine dynamometer.

The engines were initially run for at least three hours either on the dynamometer, or on the mower-decks while cutting grass. An additional two to seven hours of dynamometer run-time followed this. Emissions were monitored during dynamometer testing until stabilized (~10% coefficient of variance in brake-specific HC+NOx for three repeated measurements), which typically required between five and ten hours of total operation from the new condition, depending on the engine. The final three repeated measurements were taken as the "low hour" emission baseline.

The engines were then installed onto standard walk-behind lawn mowers. For the initial stages of field operations, a field test apparatus was constructed that could pull up to nine walk-behind mower decks simultaneously through large fields in Southeast Michigan using a garden tractor (Figures 5-11 and 5-12) to allow a more rapid accumulation of hours of operation in the field cutting grass. This was done primarily to accelerate the operation of a large number of Class I, Phase 2 lawn-mowers to generate high-hour emissions results for the purposes of generating emissions inventory data. Emissions results from the initial stages of field operation can be found in the Docket to the Nonroad SI Engine Phase 3 rule.13 The apparatus was equipped with hydraulics that lifted the front of each mower up when turning around to simulate similar turn maneuvers used during typical operation.

Subsequent stages of field operations, which included all of the Class I and Class II engines for which field data is reported in this study, were conducted in South Central Texas during the Spring of 2005 (Class II only, Figure 5-13), in Southwest Tennessee during the fall of 2005 (Class I and Class II, Figure 5-14), and in Florida in early 2006. In these stages both lawn mowers and lawn tractors were used, and they were operated by individual operators instead of using the field test apparatus. Mowing was conducted with the lawn mowers and lawn tractors in an echelon formation in large fields to prevent debris from contacting adjacent equipment. Lawn mowers and lawn tractors were also segregated to operate in different sections of each field. A total of six walk-behind lawn mowers were used in grass cutting operations until they reached approximately 110 hours of operation. Of the six lawn mowers, three used side-valve engines equipped with catalyst-mufflers, two used OHV engines equipped with catalyst-mufflers, and one used a side-valve engine equipped with an OEM muffler. The two lawn mowers equipped with OHV engines and catalyst-mufflers were also equipped with air shroud designs that directed air from the engine cooling fan that exited from the engine cylinder over the outer surface of the catalyst-muffler in a manner similar to the OEM air shroud design used with these particular lawn mowers. Three of the catalyst-muffler equipped lawn mowers (both units with the OHV engines and one with the side-valve engine) were additionally equipped with exhaust ejectors to both reduce the temperatures of the exhaust gases leaving the catalyst-muffler and to improve heat rejection from muffler and/or air shroud surfaces. Both lawn tractors were equipped with modifications to engine air shrouding and with exhaust ejectors (see Figure 5.8).

During field operation, up to eight hours of engine run-time per day was possible. Large, level fields were cut. The run sequence each day was as follows:

1. Each day started by checking the lubricating oil (and adding if necessary) and topping off the fuel tanks.

2. The engines were then started and grass cutting operations commenced. During a workday, engines were only shut down for refueling or poor weather or cutting conditions. Cutting operations ranged from 2 hours to 9 hours per day, depending on weather.

3. During refueling, oil levels were monitored, and engine oil was added if necessary. Oil consumption was monitored during the Tennessee field tests.

4. At the end of each full day of operation, debris was cleaned from the mower decks. During the initial stage of field testing (southeast Michigan), compressed air was used to clean the mower decks and intake air filters. During the later stages of field operation, mowing decks were brushed clean and air filters were not serviced between normal maintenance intervals unless a loss of engine performance was noticed by the operator. If air filter service was required between service intervals due to visible blockage, it typically involved removing the intake air filter and brushing accumulated debris from the filter prior to reinstallation (engines 243, 244, and 245 only).

5. Major maintenance consisted of changing the lubricating oil (using manufacturer-specified lubricants)d, air-filters, and spark-plugs at the manufacturers-specified intervals. When intervals were specified by season instead of hour level, 25-hours of operation was used as one season.

Field operation continued for a total of approximately 110 hours for the Class I engines and 240 hours for the Class II engines. Afterwards, the engines were removed from the lawn mowers or lawn tractors for dynamometer testing.

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[d] Lubricants were SAE 30 API SL or SAE 10w30 API SM (depending on application). Manufacturer's API specifications were API SF or better.

Figure 5-11: Field test apparatus with lawn mowers cutting grass in Southeast Michigan, late summer 2004. The apparatus was equipped hydraulic rams to lift the front of each mower to simulate turns at 10-meter intervals. The mower decks were set to a cutting height of three inches while cutting grass that was approximately five to six inches in length.

Figure 5-12: The lawn mowers were stopped for refueling, debris clean-off, and basic checks each hour. This took approximately 30 minutes, so the mowers were cycled between one hour on and half an hour off with a maximum of eight hours of actual mower running time per day, depending on weather. Regular (87 octane) unleaded pump gasoline was supplied to the work site using portable plastic gasoline cans with a trigger-nozzle, but no automatic shut off.

Figure 5-13: Lawn tractor cutting grass in Central Texas in the spring of 2005. Regular (87 octane) unleaded pump-gasoline was supplied to the work site using portable plastic gasoline cans with pour spouts. Cutting conditions were relatively dry with a high amount of debris. Grass length varied from approximately five inches to approximately 18 inches. Mower decks were set to a cutting height of approximately three inches.

Figure 5-14: Lawn mower and Lawn tractor cutting grass in Southeast Tennessee in the fall of 2005. Regular (87 octane) unleaded pump-gasoline was supplied to the work-sight using portable plastic gasoline cans with pour spouts (same fuel cans as in Texas – see Figure 11). Conditions were cool and wet with a large amount of debris. Grass length varied from approximately eight inches to approximately 18 inches. Mower decks were set to a cutting height of approximately three inches. Both wet and dry cutting conditions were encountered. Dry cutting conditions were accompanied with high levels of debris.

Figure 5-15: Lawn mower and Lawn tractor cutting grass in Florida in early 2006. Regular (87 octane) unleaded pump-gasoline was supplied to the work-sight using portable plastic gasoline cans with pour spouts. Conditions were hot and dry with tall try grass and a large amount of debris. Grass length varied from approximately five inches to approximately twelve inches. Mower decks were set to a cutting height of approximately three inches.

Acquisition of IR Thermal Images in the Field

Both still images and full-motion video infrared imaging was used to collect surface temperature data during grass cutting operations in the field in Southwest Tennessee and Florida. Full motion video infrared imaging was used to allow comparison of OEM and catalyst-equipped lawn tractors and lawn mowers while cutting grass in large (approximately 200-acre), level fields. The video IR imager was mounted onto a tripod and the cutting paths of the equipment were arranged such that one piece of equipment passed into the range of view for the imager. The operator of the imager then tracked the equipment for approximately 20 linear feet. Approximately halfway through, the equipment stopped for 5 seconds directly perpendicular to the imager at a position marked onto the turf surface to temporarily allow a higher resolution, more precise IR image for each pass in front of the imager. Passes were taken from both sides of the lawn tractors, and from the exhaust-muffler side of the lawn mowers.

Both full motion video and still imaging was used to measure surface temperatures during timed hot soaks following sustained (approximately 30-45 minutes) grass cutting with both the lawn tractors and the lawn mowers. Both full motion video and still imaging were also used to measure turf surface temperatures during extended idling of lawn tractors. Initial measurements conducted during equipment set-up that showed that Turf surface temperatures underneath and in front of the lawn tractor stabilized after approximately five minutes of idling with the engine speed setting adjusted to "high". Brief IR measurements of turf surface temperatures following 5 to 30 minutes of idling showed no significant difference versus just five minutes of idling, thus the final measurements of turf surface temperatures were taken for approximately two minutes of idling following an initial five minutes of idle for turf surface temperature stabilization.

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[1] P.A. Sandefur, W.M. Kindness, "Catalytic Converter Having a Venturi Formed From Two Stamped Components", U.S. Patent No. 5,548,955, 1996.

[2] G.J. Gracyalny, P.A. Sandefur, "Multi-Pass Catalytic Converter", U.S. Patent No. 5,732,555, 1998.

[3] Y. Yamaki, H. Kaneko, K. Nakazato, "Engine Exhaust Apparatus", U.S. Patent No. 5,431,013, 1994.

[4] A. Shiki, M. Nakano, H. Nakazima, "Muffler with Catalyst for Internal Combustion Engine", U.S. Patent No. 4,579,194, 1986.

[5] V. Vavilov, V. Demin, "Infrared thermographic inspection of operating smokestacks", Infrared Physics & Technology, Volume 43, Issues 3-5 , June 2002, Pages 229-232.

[6] R. Monti, G. P. Russo, "Non-intrusive methods for temperature measurements in liquid zones in microgravity environments", Institute of Aerodynamics ", Acta Astronautica, Volume 11, Issue 9 , September 1984, Pages 543-551.

[7] H. Wiggenhauser, "Active IR-applications in civil engineering", Infrared Physics & Technology, Volume 43, Issues 3-5 , June 2002, Pages 233-238.

[8] Title 40, U.S. Code of Federal Regulations, Part 90, Subpart E, Appendix A.

[9] S. Mizusawa, "Silencer for and Internal Combustion Engine", U.S. Patent No. 4,124,091, 1978.

[10] Title 16, U.S. Code of Federal Regulations, Part 1205.

[11] ANSI B71.1-2003, "American National Standard for Consumer Turf Care Equipment – Walk-Behind Mowers and Ride-On Machines with Mowers – Safety Specifications".

[12] "Control of Emissions From Nonroad Spark-Ignition Engines, Vessels, and Equipment Document", Docket ID "EPA-HQ-OAR-2004-0008-0089", tests 1514-4, 1514-5 and 1514-6.

[13] "Control of Emissions From Nonroad Spark-Ignition Engines, Vessels, and Equipment Document", Docket ID "EPA-HQ-OAR-2004-0008-0089".

6. Test Results—Comparison between EPA's Phase 3 Prototypes and Current Engine Systems

In this chapter we will discuss the results of laboratory and field testing of the Class I and Class II engines described in Chapter 5, tables 5-1 and 5-2, respectively.

A. EMISSIONS RESULTS

A summary of the exhaust emissions results for the tested engine configurations over the EPA A-cycle may be found in Appendix B. Emissions levels of all of the catalyst-configured systems tested were consistent with the California Tier 3 and the expected Federal Phase 3 emission standards. In many cases, HC+NOx emissions were well below the expected Phase 3 standards. An increase in exhaust back-pressure was expected with the addition of catalyst-mufflers to the engines, but engine power output and load response was comparable to that of the engines using OEM mufflers.

B. LABORATORY TEST RESULTS

Surface temperature measurements by infrared thermal imaging – Class I Side-valve Engines

Engine 258:

Figure 6-1 shows infrared thermal images for A-cycle modes 1, 3 and 5 taken during laboratory testing of engine 258 with a catalyst-muffler and with an OEM muffler following approximately 10 hours of engine break-in and catalyst "degreening".[e] The catalyst-muffler used was the European catalyst-muffler with the stamped secondary-air-venturi, modified to increase the catalyst substrate volume to approximately 40 cc (2-20 cc 400 cpsi ceramic monoliths, similar to the "middle" unit in Figure 5-2) as described in Chapter 5. The peak temperatures on the catalyst-muffler were near the exhaust outlet. The through-bolts attaching the muffler to the engine and one of the welds between the outer and inner halves of the catalyst-muffler were also at similar temperatures to the outlet. This particular weld was a result of modifications made to the muffler to increase catalyst volume. Production mufflers typically use a folded seam rather than a continuous weld to join stamped halves together, and folded seams tend to hold in less heat.

The peak temperatures for the OEM muffler were at the muffler through-bolts and the lower half of the outside surface of the muffler, immediately downstream of where the exhaust expands through the muffler baffle. The OEM muffler peak temperatures were significantly hotter than those of the catalyst-muffler at all six of the A-cycle test modes, which covered the entire operational range of the engine. The heat-affected surface area above 350 °C covers a larger area of the OEM muffler at high load than was the case for the catalyst-muffler. While cooler temperatures of the catalyst-muffler versus the OEM muffler initially seem counterintuitive, the catalyst-muffler has a number of design elements that allow it to reject heat more effectively than the OEM muffler, including:

1. The catalyst-muffler routes the exhaust gases through three stages of baffles (two pre-catalyst, one post-catalyst) vs. a single stage baffle for the OEM muffler.
2. The catalyst-muffler has approximately double the external surface area of the OEM muffler to reject heat over.
3. The catalyst-muffler has a longer internal path (including one flow reversal) to reject heat through.
4. Approximately 25% of the catalyst-muffler surface area is located directly in the cooling air-flow of the engine fan immediately downstream of the cylinder fins. Very little cooling air reaches the OEM muffler due to its positioning well forward of where much of the cooling air exhausts from the engine.

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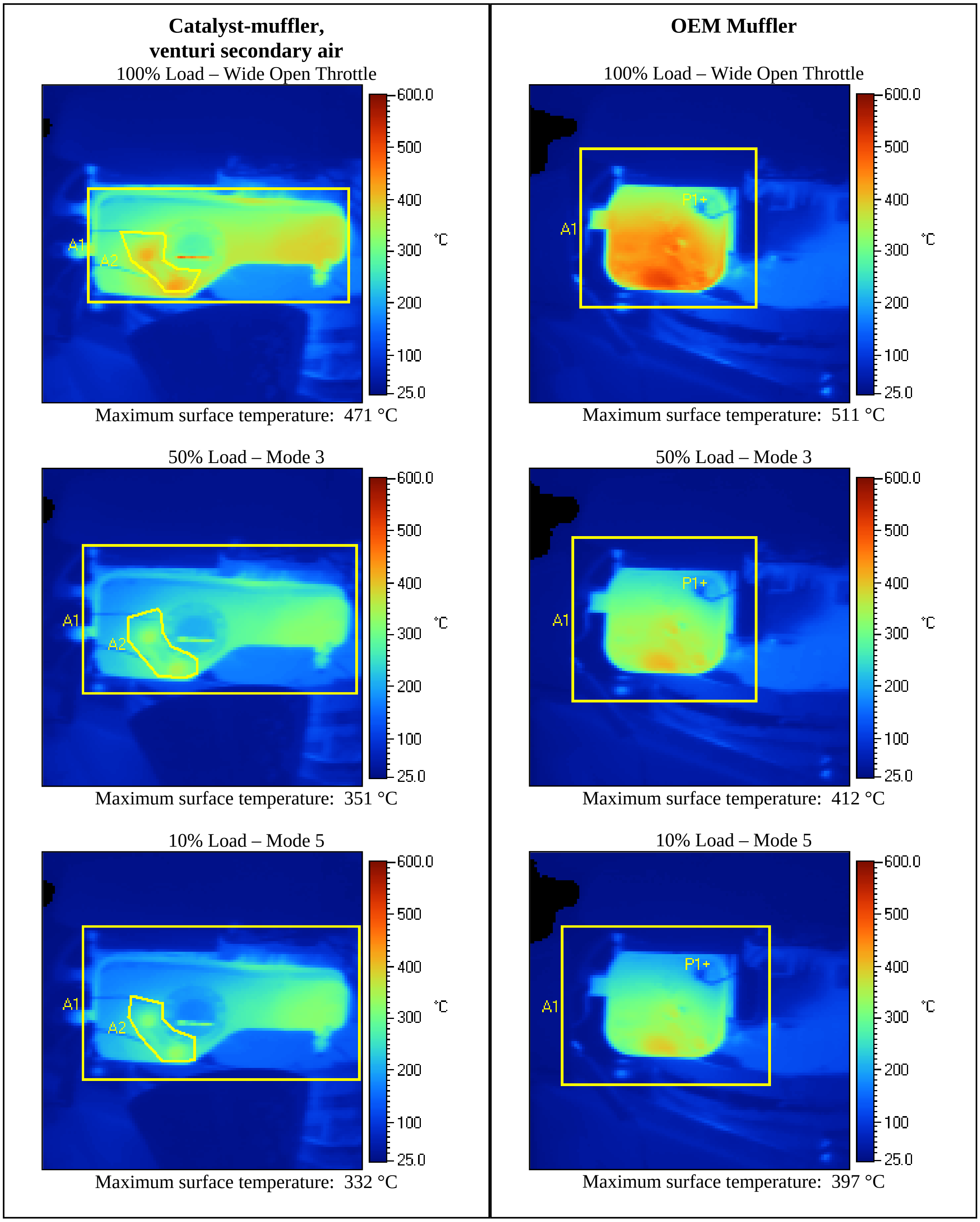
[e] Catalyst degreening involves operation of a catalyst in engine exhaust long enough for an initial degree of thermal sintering of PGM to occur. This was performed for emissions testing purposes only.

Engine 236

Figure 6-2 shows infrared thermal images for A-cycle modes 1, 3 and 5 taken during laboratory testing of engine 236 following approximately 10 hours of engine break-in and catalyst “degreening”. The catalyst-muffler was similar in construction to the one used with engine 258 except that the catalyst used a 200 cpsi, 44 cc metal monolith with a tri-metallic washcoating formulation, and the inlet location was changed to allow fitment to engine 236 since this engine is from a different engine family than engine 258.

This engine had peak OEM-muffler temperatures that were 50 to 60 degrees higher than that of engine 258. As a result, both the catalyst-muffler and OEM muffler surface temperatures were higher for engine 236 than what was observed for engine 258. Comparing the catalyst-muffler in figure 6-2 to that in figure 6-1, the section of the catalyst-muffler containing the catalyst substrate was considerably hotter than that in figure 6-1, in part due to lower air-flow rate from the cooling fan and higher cooling air temperatures for engine 236 relative to engine 258. The OEM cooling fan was integral to the flywheel and used six constant cross section flat-paddle-type blades. There is substantial potential to reduce catalyst-muffler surface temperatures for engine 236 via use of a higher efficiency, higher volume cooling fan and by paying close attention to the routing of cooling air-flow relative to the muffler position.

As with engine 258, the peak surface temperatures with catalyst-muffler were significantly cooler than those of the OEM muffler at each of the A-cycle test points. The hottest areas of the catalyst-muffler were the portion of the muffler that contained the catalyst substrate (the area center-right of the images) and the continuous weld running along the top of the catalyst-muffler. The hottest area of the OEM muffler was on the outer surface directly opposite from the exhaust port outlet. The heat-affected surface area above 350 °C was comparable for the OEM muffler and the catalyst-muffler.



Catalyst-muffler, venturi secondary air

100% Load – Wide Open Throttle

Maximum surface temperature: 471 °C

50% Load – Mode 3

Maximum surface temperature: 351 °C

10% Load – Mode 5

Maximum surface temperature: 332 °C

OEM Muffler

100% Load – Wide Open Throttle

Maximum surface temperature: 511 °C

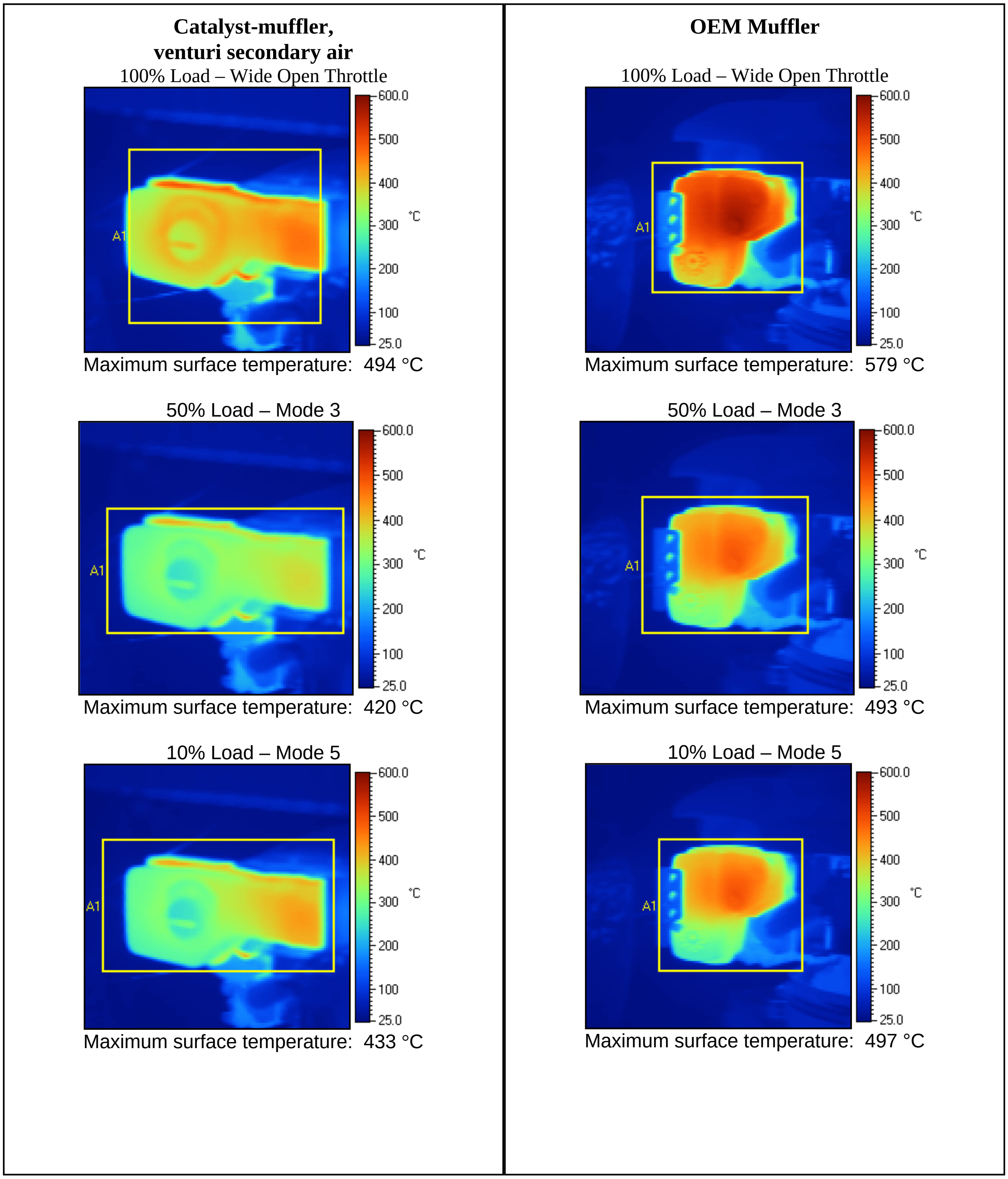
50% Load – Mode 3

Maximum surface temperature: 412 °C

10% Load – Mode 5

Maximum surface temperature: 397 °C

Figure 6-1: Infrared thermal images showing the surface temperatures of exhaust system components for side-valve engine 258 at low hours, equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle.



Catalyst-muffler, venturi secondary air

100% Load – Wide Open Throttle

Maximum surface temperature: 494 °C

50% Load – Mode 3

Maximum surface temperature: 420 °C

10% Load – Mode 5

Maximum surface temperature: 433 °C

OEM Muffler

100% Load – Wide Open Throttle

Maximum surface temperature: 579 °C

50% Load – Mode 3

Maximum surface temperature: 493 °C

10% Load – Mode 5

Maximum surface temperature: 497 °C

Figure 6-2: Infrared thermal images showing the surface temperatures of exhaust system components for side-valve engine 236 at low hours, equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle.

Infrared thermal imaging – Class I OHV Engines

In some respects, Class I OHV engines present more of a design challenge with respect to exhaust component heat rejection than their side-valve counterparts. Peak exhaust gas temperatures measured at the muffler inlet can be 50-100 °C higher at some operating conditions when compared to side-valve engines used in similar walk-behind lawn mower applications. In some cases, OEM muffler configurations tested incorporated shrouds around the muffler to enhance heat rejection via forced convection using cooling air from the engine cooling fan (engines 243 and 244). Other OEM muffler designs for OHV engines were generally similar to those used with side-valve engines (engines 241, 255). The shrouded designs maintained a minimum clearance between the muffler and the shroud to prevent debris accumulation, similar to the clearances used to prevent debris accumulation within the engine shrouding of the cylinder and cylinder-head. The catalyst-muffler configurations tested by EPA with engines 243 and 244 incorporated similar shrouding, and in one case (engine 243) used a modified OEM air-shroud.

Engine 241

Figure 6-3 shows infrared thermal images for A-cycle modes 1, 3 and 5 acquired during laboratory testing of engine 241 following approximately 110 hours of dynamometer aging (near the end of useful life). The catalyst-muffler used was similar to that used with engine 258 (40 cc, 400 cpsi ceramic monolith, top of figure 5-2). The muffler baffles and muffler inlet were reconfigured, and the muffler did not use through-bolts exposed to the exhaust flow. No modifications were made to the stamped secondary-air venturi. The exhaust gas temperatures for this OHV engine family were typically higher than those observed for side-valve engines (e.g., engine 258). Peak surface temperatures for the catalyst-muffler occurred on the outer muffler shell, immediately downstream of the catalyst substrate, and on the weld along the lower parting seam of the muffler shell. Peak surface temperatures for the OEM muffler occurred along the outer-most surface of the muffler shell and near the stub-pipe exhaust outlet. Peak surface temperatures for the catalyst-muffler were cooler than the OEM muffler for the 100% load, WOT condition, and were comparable to the OEM muffler over the remaining steady-state operating conditions of the A-cycle. The OEM muffler's highest surface temperatures generally covered a larger surface area of the outer muffler shell than was the case for the catalyst-muffler.

Hot soak tests conducted from the 100% load WOT condition show the catalyst-muffler cooler than the OEM muffler for the first 30 seconds following shutdown (figure 6-4). At one minute following shutdown from WOT, the temperature decay of the catalyst-muffler decreased due to conductive heat transfer from the internal surfaces to the outer surfaces of the catalyst-muffler. Thus at 30 seconds after shutdown from WOT, the catalyst-muffler peak temperatures were approximately the same temperature as the OEM muffler rather than cooler, and at one minute following shutdown, the catalyst-muffler peak temperatures were approximately 80 °C higher than the OEM muffler. After approximately two minutes following shutdown from the WOT condition, peak temperatures for the catalyst-muffler were again comparable to the OEM muffler (figures 6-4 and 6-5).

During hot-soak tests from the 50% load point (mode 3), surface temperatures of the catalyst-muffler and OEM muffler were comparable throughout the hot-soak period (figures 6-6 and 6-7). The initial hot-soak temperatures obtained following sustained 50% load operation were also more comparable to exhaust system peak surface temperatures measured field operation. After approximately 2-minutes following shut-down from 50% load, peak temperatures of both the OEM muffler and the catalyst-muffler were below 250 °C, which is approximately the auto-ignition temperature of gasoline. This corresponded well to the manufacturer's recommendations within the Owner's Manual for this engine that the operator wait two minutes following shut-down before removing the cap to the fuel tank for refueling.

Engine 255

Figure 6-8 shows infrared thermal images for A-cycle modes 1, 3, and 5 acquired during laboratory testing of engine 255 with a catalyst-muffler and with an OEM muffler following approximately 10 hours of engine break-in and catalyst "degreening". The catalyst-muffler used was the same unit shown in figure 5-6. Although engine 255 is from the same engine family as engine 241, the catalyst-muffler has several key differences. In order to simultaneously enhance emission control performance and heat rejection, part of the catalyst volume was relocated upstream of the secondary-air-venturi by mounting a catalyzed-tube pre-catalyst in the short length of exhaust pipe between the exhaust port and the entrance to the muffler body. The catalyst substrate size was reduced, the cell density was halved, and a metal monolith construction was substituted for the cordierite monoliths used with engine 241. A tri-metallic washcoating formulation was used, although PGM loading was similar to that used with engine 241 on a per-unit of catalyst volume basis. The increased catalyst efficiency of this catalyst-muffler configuration allowed a reduction in secondary-air entrainment. Two of the four air inlet holes in the stamped venturi were blocked to reduce the volume of secondary-air flow drawn by the stamped venturi. In the end, the level of HC+NOx emissions control for the catalyst-muffler tested with engine 255 was approximately equivalent to the system tested with engine 241, but with approximately 50% less secondary air flow, and an overall reduction in total catalyst volume and PGM. CO oxidation at low operational hours was reduced from approximately 50% over the A-cycle to approximately 15%.

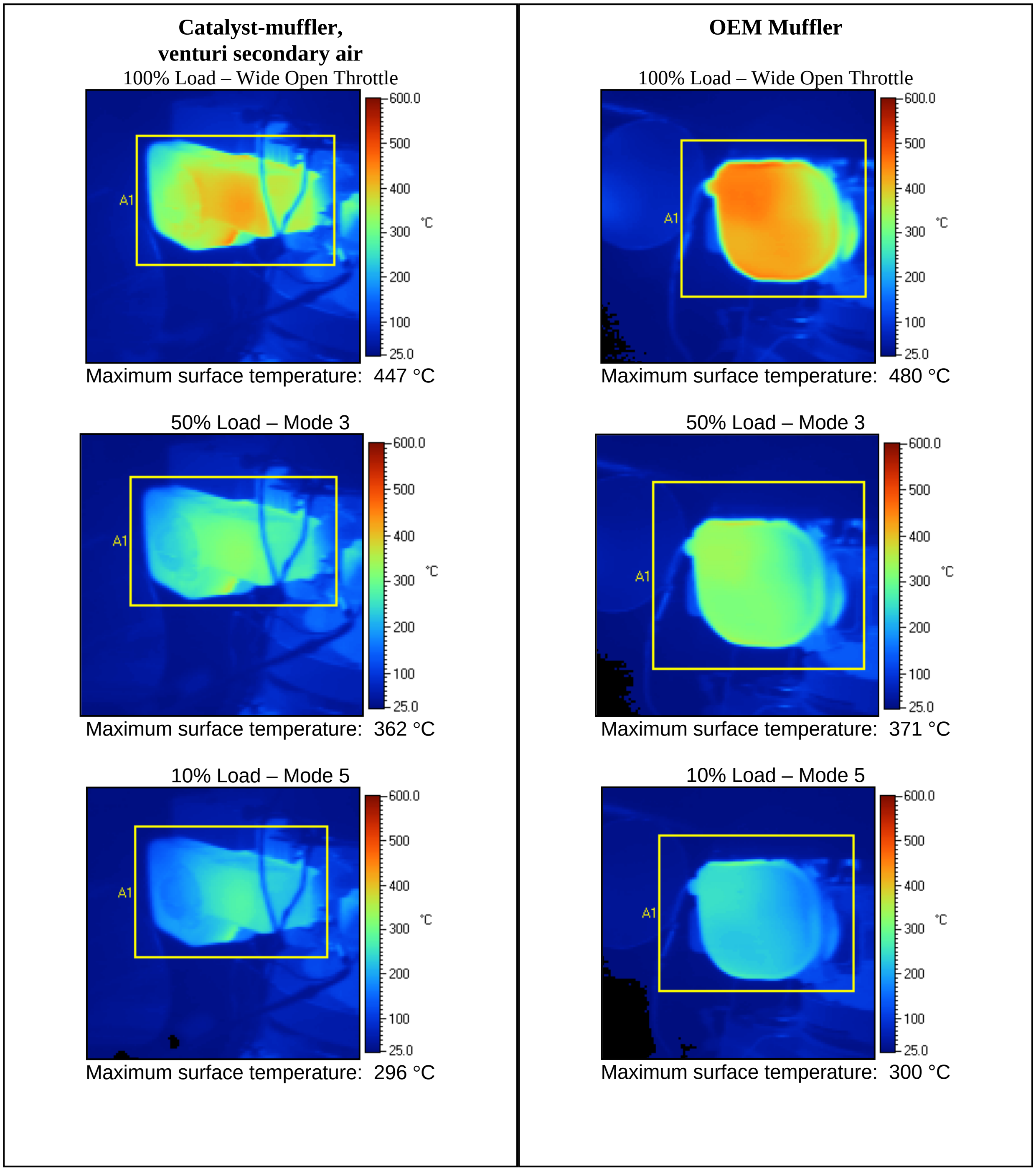
Peak surface temperatures for the catalyst-muffler were in the area where the exhaust flow turns 180 degrees, between the catalyst outlet and the muffler outlet. Peak surface temperatures for the OEM muffler were on the outer-surface near where the exhaust expands through the muffler baffles. The peak surface temperatures of the catalyst-muffler were approximately 30 to 60 degrees cooler than the OEM muffler for all six modes of the A-cycle test and were also reduced relative to the catalyst-muffler tested with engine 241. The heat-affected surface area above 350 °C for the catalyst-muffler was comparable to that of the OEM muffler.

Engine 244

Figure 6-9 shows infrared thermal images for A-cycle modes 1, 3, and 5 acquired during laboratory testing of engine 244 with a catalyst-muffler and with an OEM muffler following approximately 10 hours of engine break-in and catalyst "degreening". The catalyst-muffler used was similar to that used with engine 258, but with a different catalyst (44 cc, 200 cpsi metal monolith, tri-metallic washcoating formulation). The muffler baffles and muffler inlet were reconfigured, and the muffler did not use through-bolts exposed to the exhaust flow. A steel shroud was fabricated to route air-flow over the catalyst-muffler in a manner similar to that of the OEM muffler and shroud used with this engine. An exhaust ejector was incorporated into the catalyst-muffler shroud design to cool the muffler outlet (the hottest part on the OEM muffler configuration) and to provide additional cooling to the exhaust gases exiting the catalyst-muffler. The use of the ejector dropped the peak temperature of exposed surfaces by approximately 200 °C relative to the OEM configuration over the six modes of the A-cycle test. Exposed surfaces were below the auto-ignition point of gasoline (~250 °C) at all of the tested conditions, including WOT. The tested catalyst-muffler configuration maintained 100-200 °C cooler exposed peak surface temperatures for the entire five minute timed hot-soak period for hot soaks from both the WOT (see Figures 6-10 and 6-11) and 50% load (see Figures 6-12 and 6-13) conditions when compared to the OEM configuration. The peak temperatures of the shroud used with the catalyst-muffler increased slightly during the first minute following engine shut-down, and then decreased throughout the remainder of the timed soak period.

Engine 243

The tests conducted with engine 244 were repeated with a nearly identical engine (engine 243) that also incorporated further improvements in the design of the catalyst-muffler, air shrouding and exhaust ejector. A completely different muffler design was used which included a new concentric tube venturi. During development, secondary-air flow was progressively reduced to minimize CO while maintaining HC+NOx control above 40% efficiency over the A-cycle. The size reduction of the muffler enabled by the improvements allowed use of a modified version of the OEM muffler shroud. The exhaust ejector was lengthened approximately 25% to increase the draw of air through the ejector. The changes resulted in reduced CO oxidation and a further 20 to 40 °C reduction in external surface temperatures relative to the catalyst-muffler and shroud configuration tested with engine 244 (figure 6-14). Peak temperatures of exposed surfaces were below 200 °C for all operating points, including the region near the exhaust outlet from the ejector. During the hot soak from the WOT condition, peak surface temperatures were similar to the catalyst-muffler tested with engine 244 and approximately 200 °C cooler than peak temperatures with the OEM system (figures 6-15 and 6-16). Peak temperatures during hot-soak from the 50% load condition were 20-40 °C cooler than the earlier catalyst-muffler configuration, and approximately 100-300 °C cooler than the OEM system (figures 6-17 and 6-18).



Catalyst-muffler, venturi secondary air

100% Load – Wide Open Throttle

Maximum surface temperature: 447 °C

50% Load – Mode 3

Maximum surface temperature: 362 °C

10% Load – Mode 5

Maximum surface temperature: 296 °C

OEM Muffler

100% Load – Wide Open Throttle

Maximum surface temperature: 480 °C

50% Load – Mode 3

Maximum surface temperature: 371 °C

10% Load – Mode 5

Maximum surface temperature: 300 °C

Figure 6-3: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 241 at high hours, equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle.

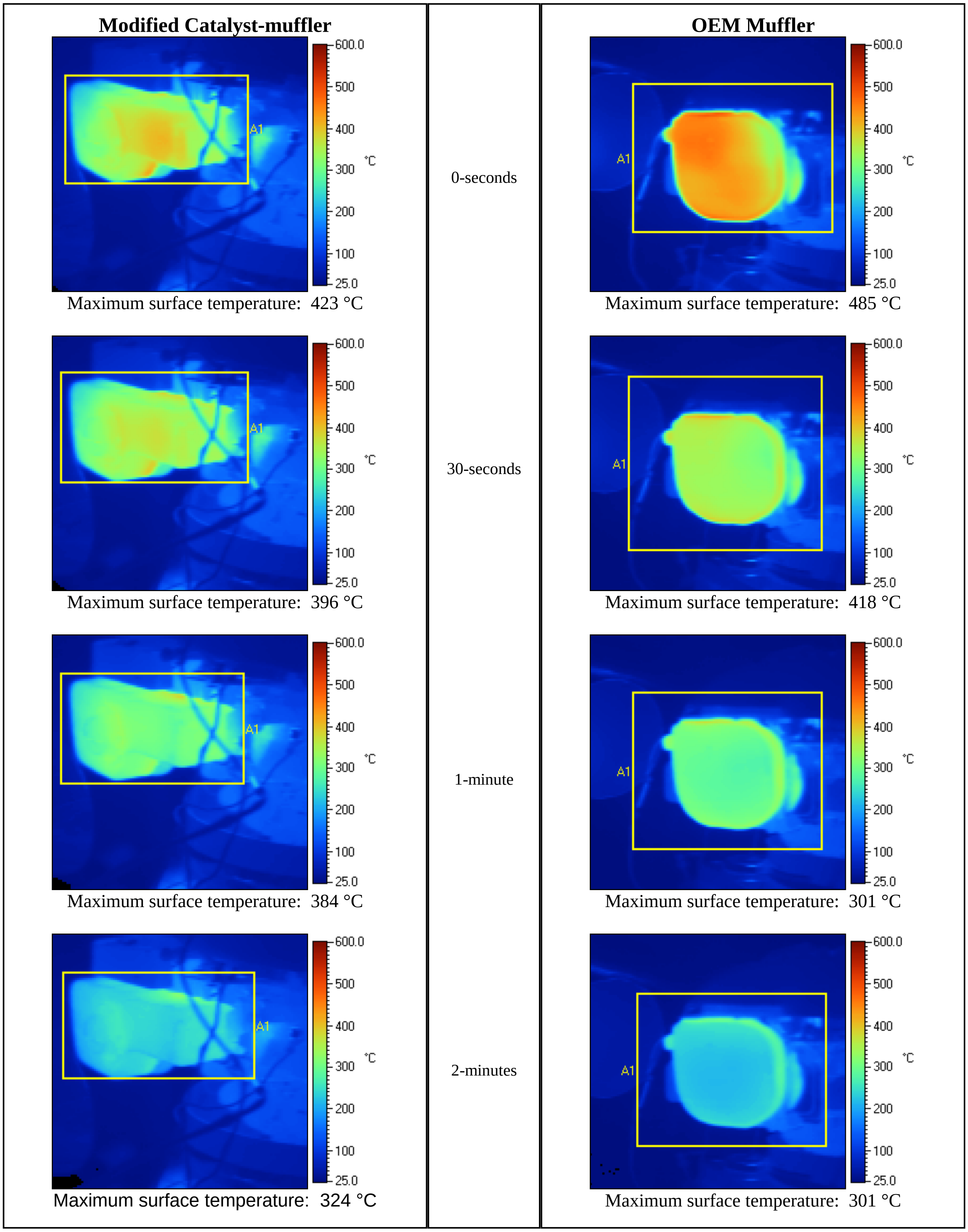


Figure 6-4: Infrared thermal images showing the surface temperatures of exhaust system components for engine 241 during a hot-soak period immediately after engine shutdown from sustained operation at WOT, 100% load (A-cycle mode 1).

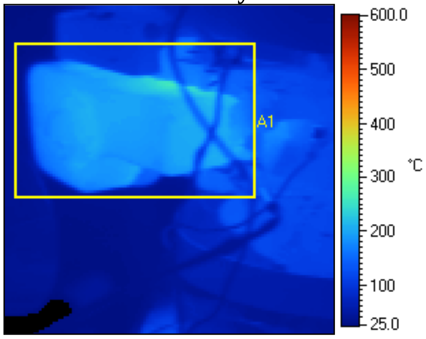
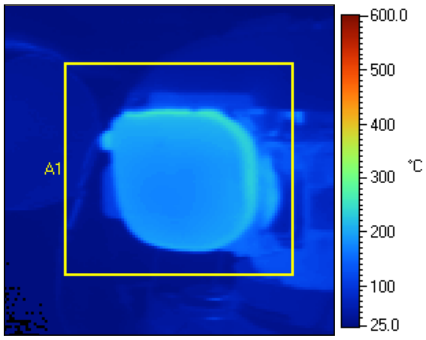
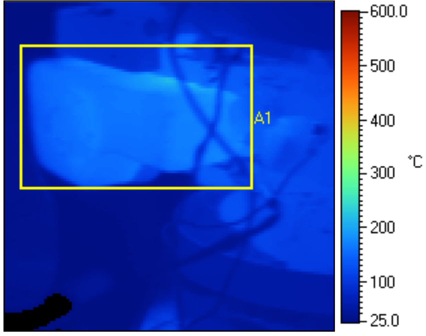
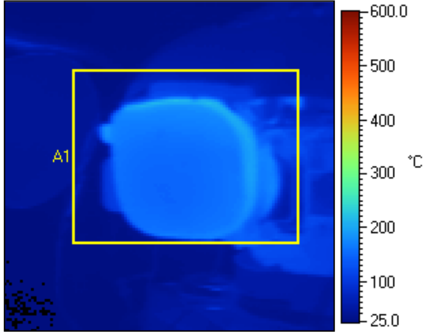
Modified Catalyst-muffler		**OEM Muffler**
 Maximum surface temperature: 265 °C	3-minutes	 Maximum surface temperature: 258 °C
 Maximum surface temperature: 219 °C	4-minutes	 Maximum surface temperature: 218 °C

Figure 6-5: Continuation of the hot-soak shown in figure 6-4.

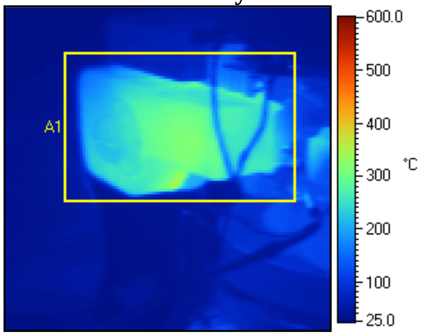
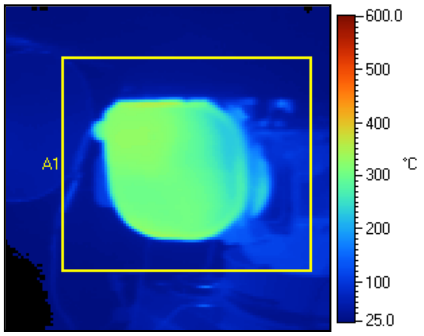
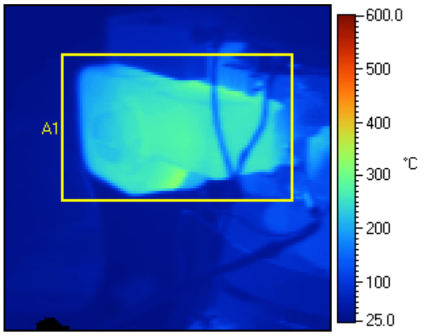
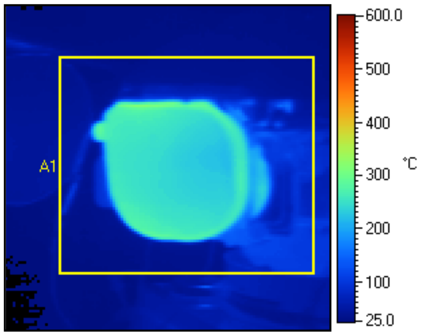
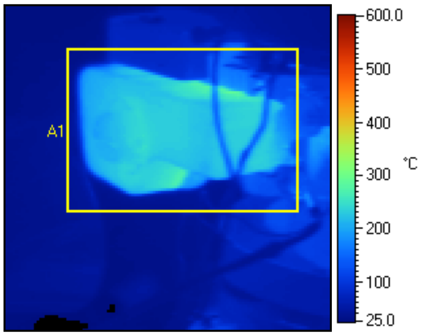
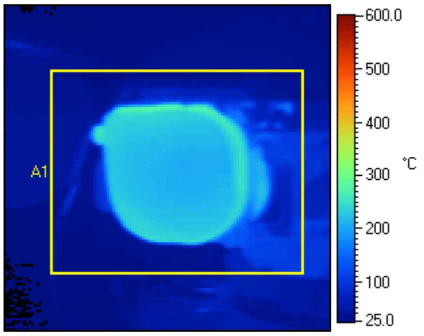
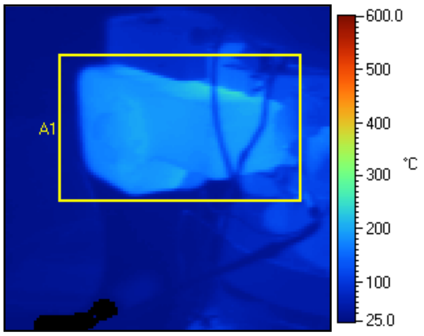
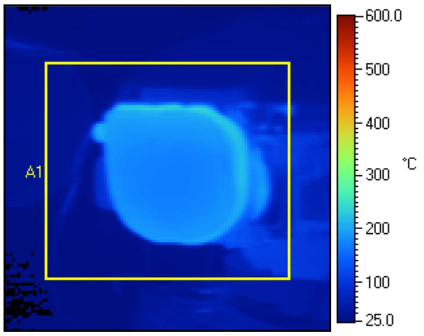
Modified Catalyst-muffler		**OEM Muffler**
 Maximum surface temperature: 351 °C	0-seconds	 Maximum surface temperature: 360 °C
 Maximum surface temperature: 325 °C	30-seconds	 Maximum surface temperature: 318 °C
 Maximum surface temperature: 290 °C	1-minute	 Maximum surface temperature: 288 °C
 Maximum surface temperature: 247 °C	2-minutes	 Maximum surface temperature: 242 °C

Figure 6-6: Infrared thermal images showing the surface temperatures of exhaust system components for engine 241 during a hot-soak period immediately after engine shutdown from sustained operation at 50% load (A-cycle mode 3).

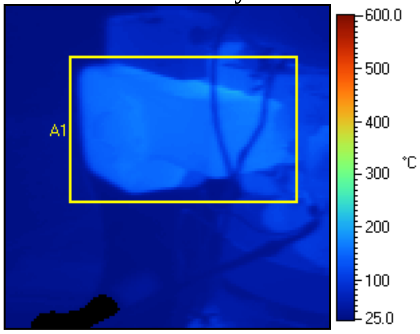
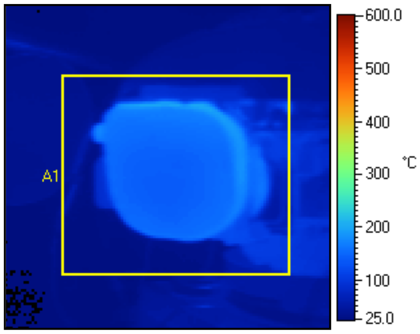
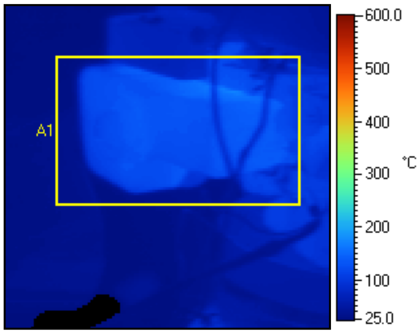
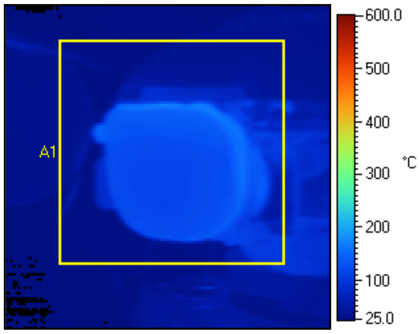
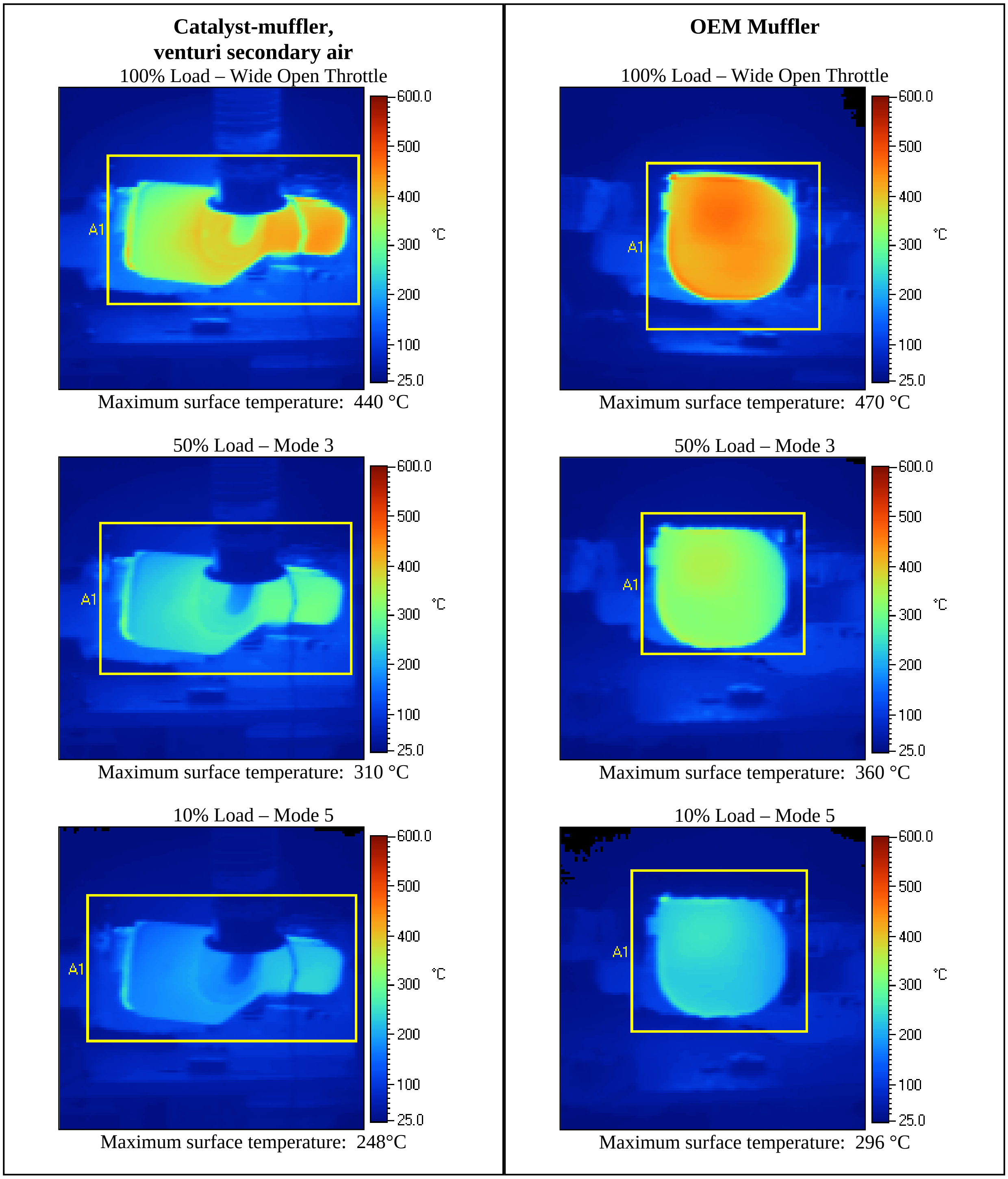
Modified Catalyst-muffler		OEM Muffler
 Maximum surface temperature: 206 °C	3-minutes	 Maximum surface temperature: 207 °C
 Maximum surface temperature: 176 °C	4-minutes	 Maximum surface temperature: 173 °C

Figure 6-7: Continuation of the hot-soak shown in figure 6-6.



Catalyst-muffler, venturi secondary air

100% Load – Wide Open Throttle

Maximum surface temperature: 440 °C

50% Load – Mode 3

Maximum surface temperature: 310 °C

10% Load – Mode 5

Maximum surface temperature: 248°C

OEM Muffler

100% Load – Wide Open Throttle

Maximum surface temperature: 470 °C

50% Load – Mode 3

Maximum surface temperature: 360 °C

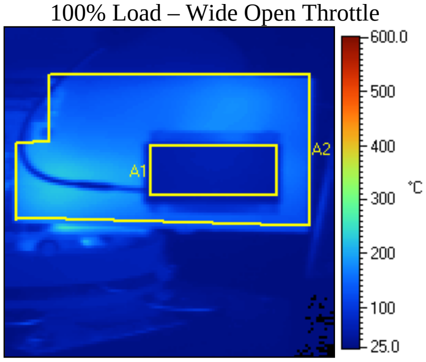
10% Load – Mode 5

Maximum surface temperature: 296 °C

Figure 6-8: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 255 at low hours, equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle.

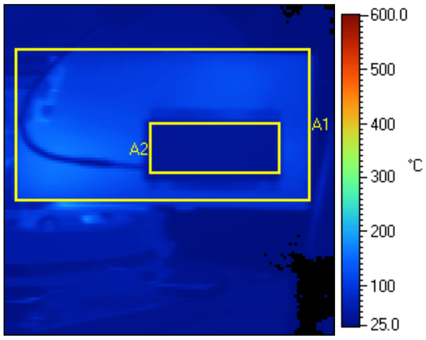
Catalyst-muffler,
venturi secondary air

100% Load – Wide Open Throttle



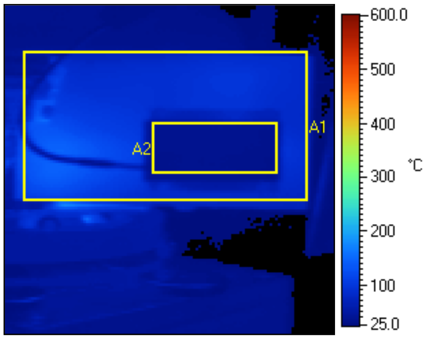
Maximum surface temperature: 230 °C

50% Load – Mode 3



Maximum surface temperature: 102 °C

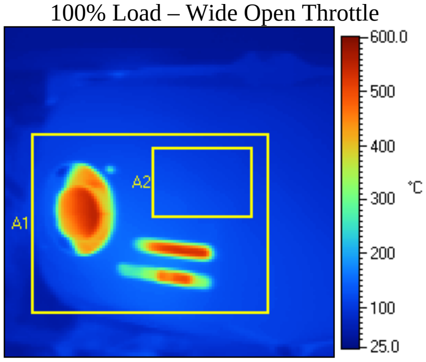
10% Load – Mode 5



Maximum surface temperature: 161 °C

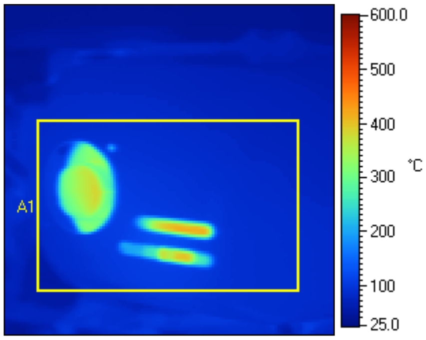
OEM Muffler

100% Load – Wide Open Throttle



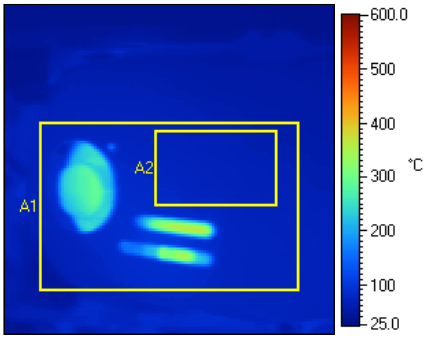
Maximum surface temperature: 551 °C

50% Load – Mode 3



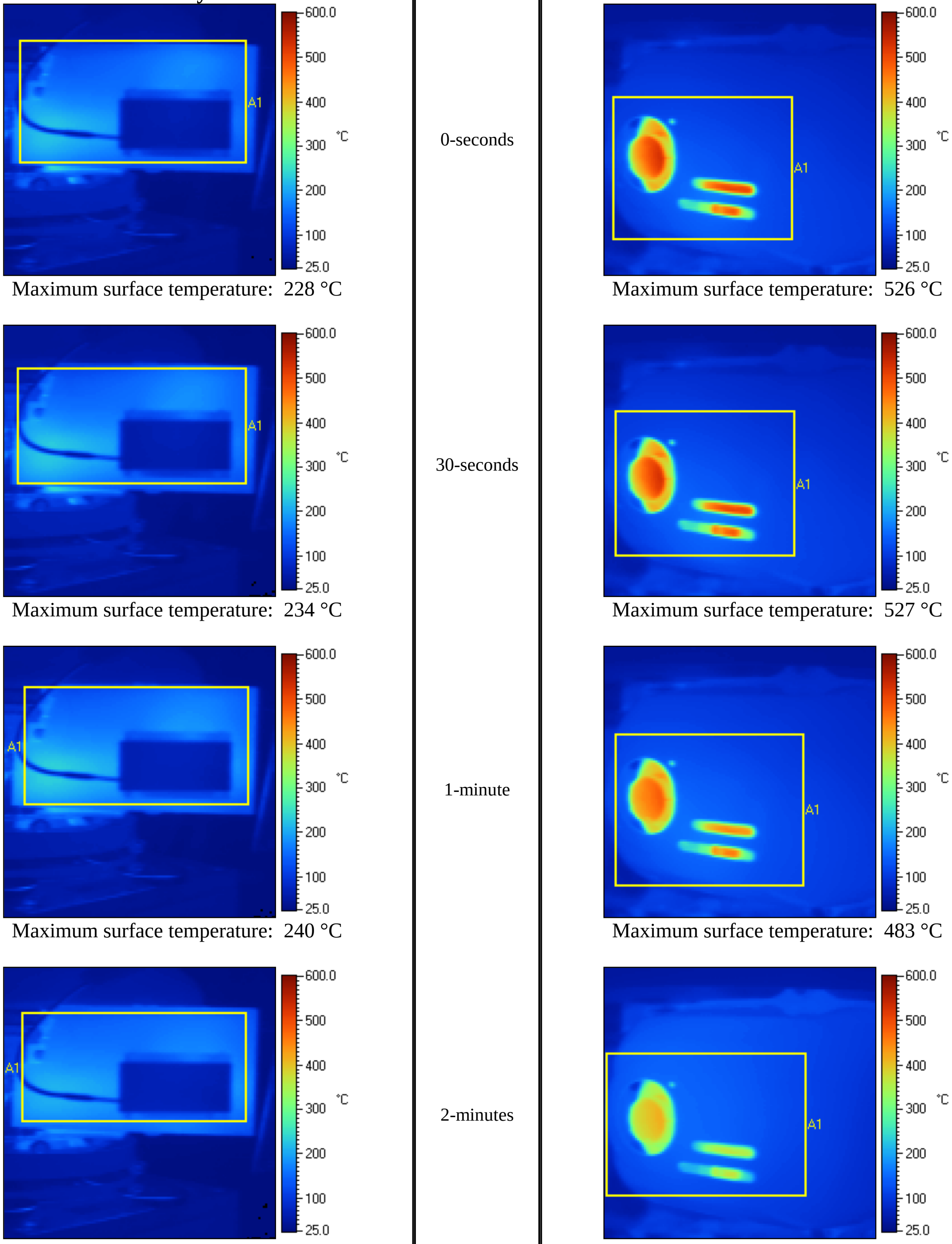
Maximum surface temperature: 421 °C

10% Load – Mode 5



Maximum surface temperature: 363 °C

Figure 6-9: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 244 at high hours, equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle. The OEM muffler configuration was equipped with a full shroud that directed air-flow over the muffler. This configuration was largely reproduced for the catalyst-muffler. An exhaust-ejector was also added for improved shroud and exhaust-gas cooling (dark blue rectangular area).



Modified Catalyst-muffler		OEM Muffler
Maximum surface temperature: 228 °C	0-seconds	Maximum surface temperature: 526 °C
Maximum surface temperature: 234 °C	30-seconds	Maximum surface temperature: 527 °C
Maximum surface temperature: 240 °C	1-minute	Maximum surface temperature: 483 °C
Maximum surface temperature: 215 °C	2-minutes	Maximum surface temperature: 418 °C

Figure 6-10: Infrared thermal images showing the surface temperatures of exhaust system components for engine 244 during a hot-soak period immediately after engine shutdown from sustained operation at WOT, 100% load (A-cycle mode 1).

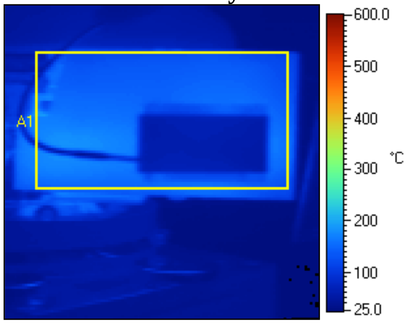
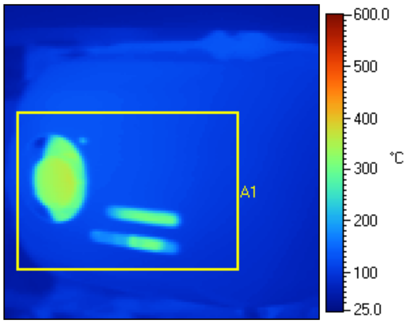
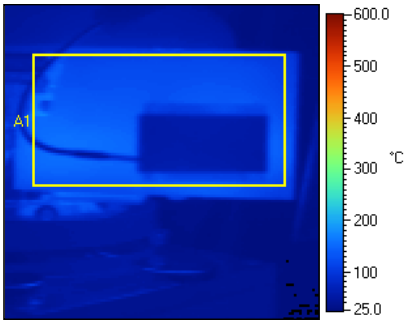
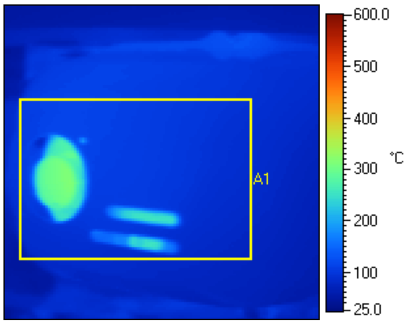
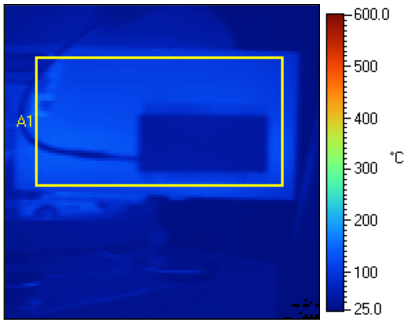
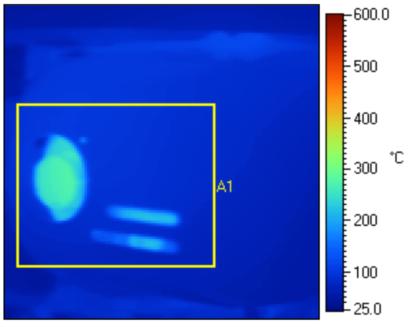
Modified Catalyst-muffler		**OEM Muffler**
 Maximum surface temperature: 196 °C	3-minutes	 Maximum surface temperature: 363 °C
 Maximum surface temperature: 180 °C	4-minutes	 Maximum surface temperature: 319 °C
 Maximum surface temperature: 164 °C	5-minutes	 Maximum surface temperature: 280 °C

Figure 6-11: Continuation of the hot-soak shown in figure 6-10.

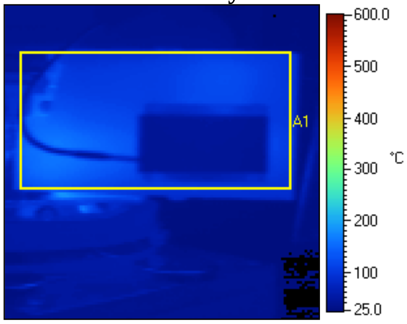
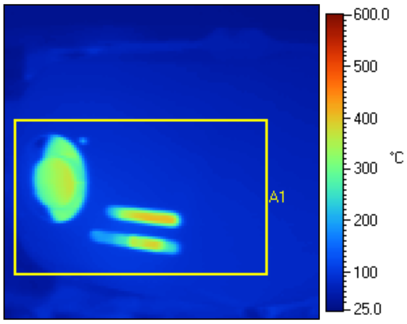
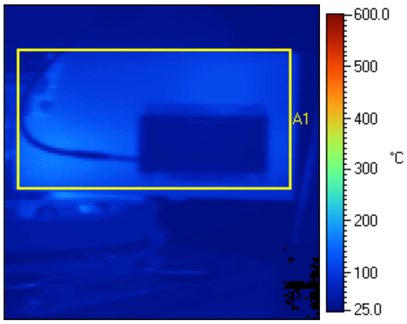
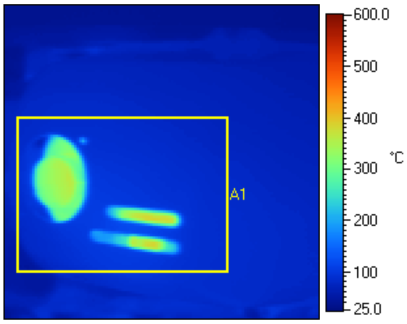
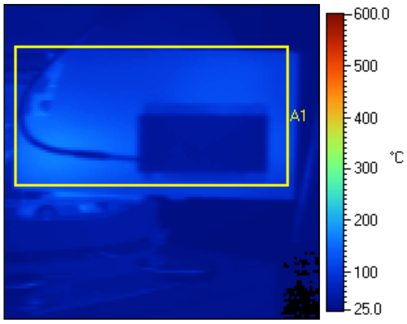
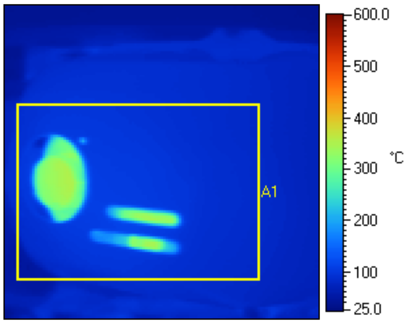
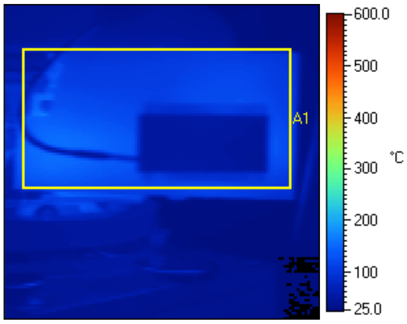
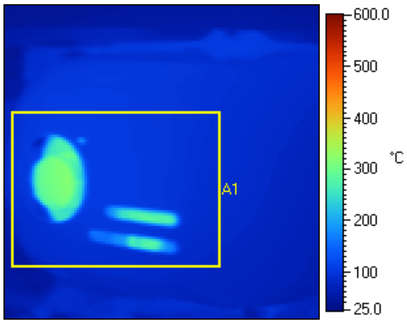
Modified Catalyst-muffler		**OEM Muffler**
 Maximum surface temperature: 168 °C	0-seconds	 Maximum surface temperature: 411 °C
 Maximum surface temperature: 173 °C	30-seconds	 Maximum surface temperature: 389 °C
 Maximum surface temperature: 176 °C	1-minute	 Maximum surface temperature: 357 °C
 Maximum surface temperature: 169 °C	2-minutes	 Maximum surface temperature: 321 °C

Figure 6-12: Infrared thermal images showing the surface temperatures of exhaust system components for engine 244 during a hot-soak period immediately after engine shutdown from sustained operation at 50% load (A-cycle mode 3).

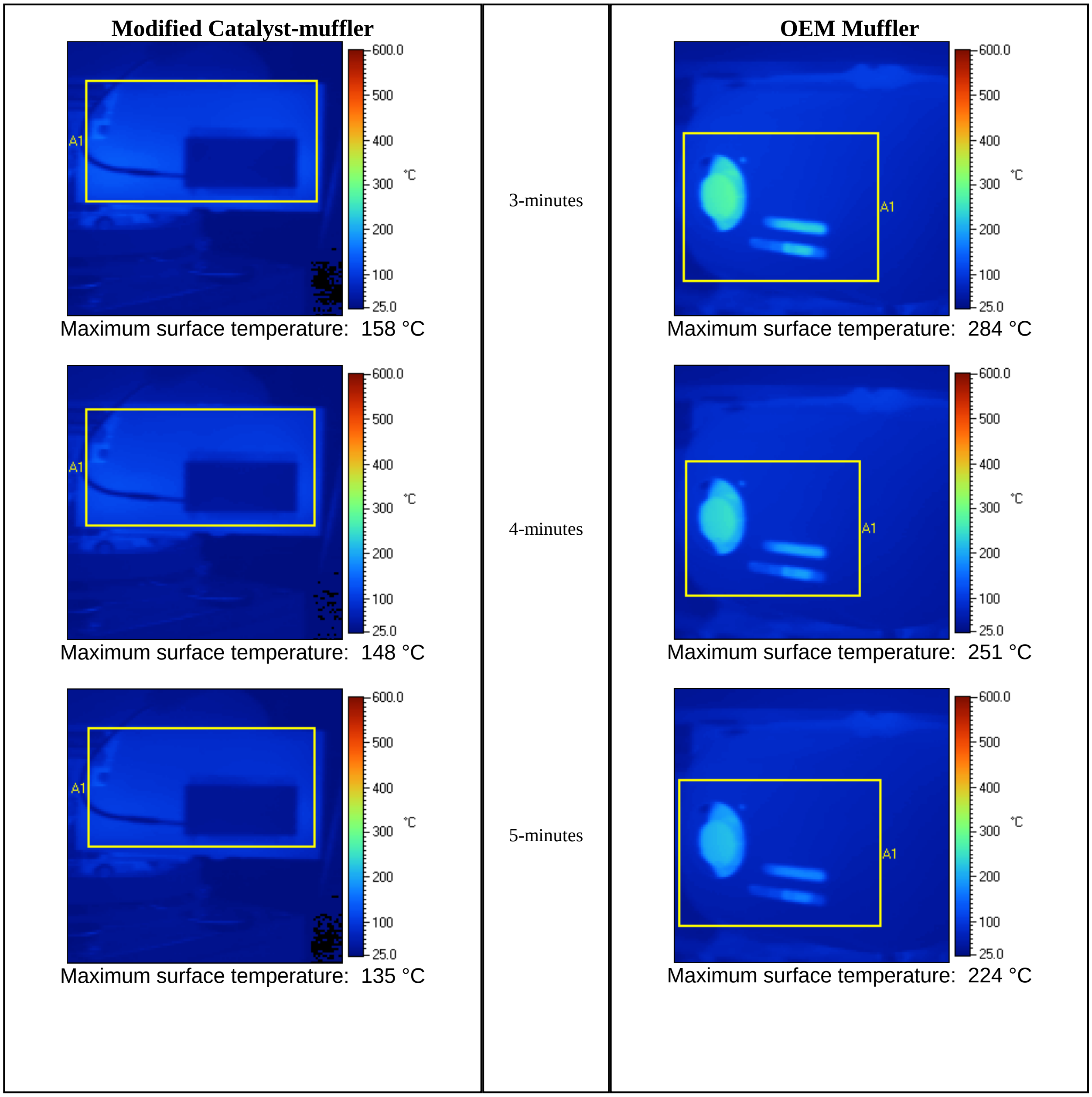


Figure 6-13: Continuation of the hot-soak shown in figure 6-12.

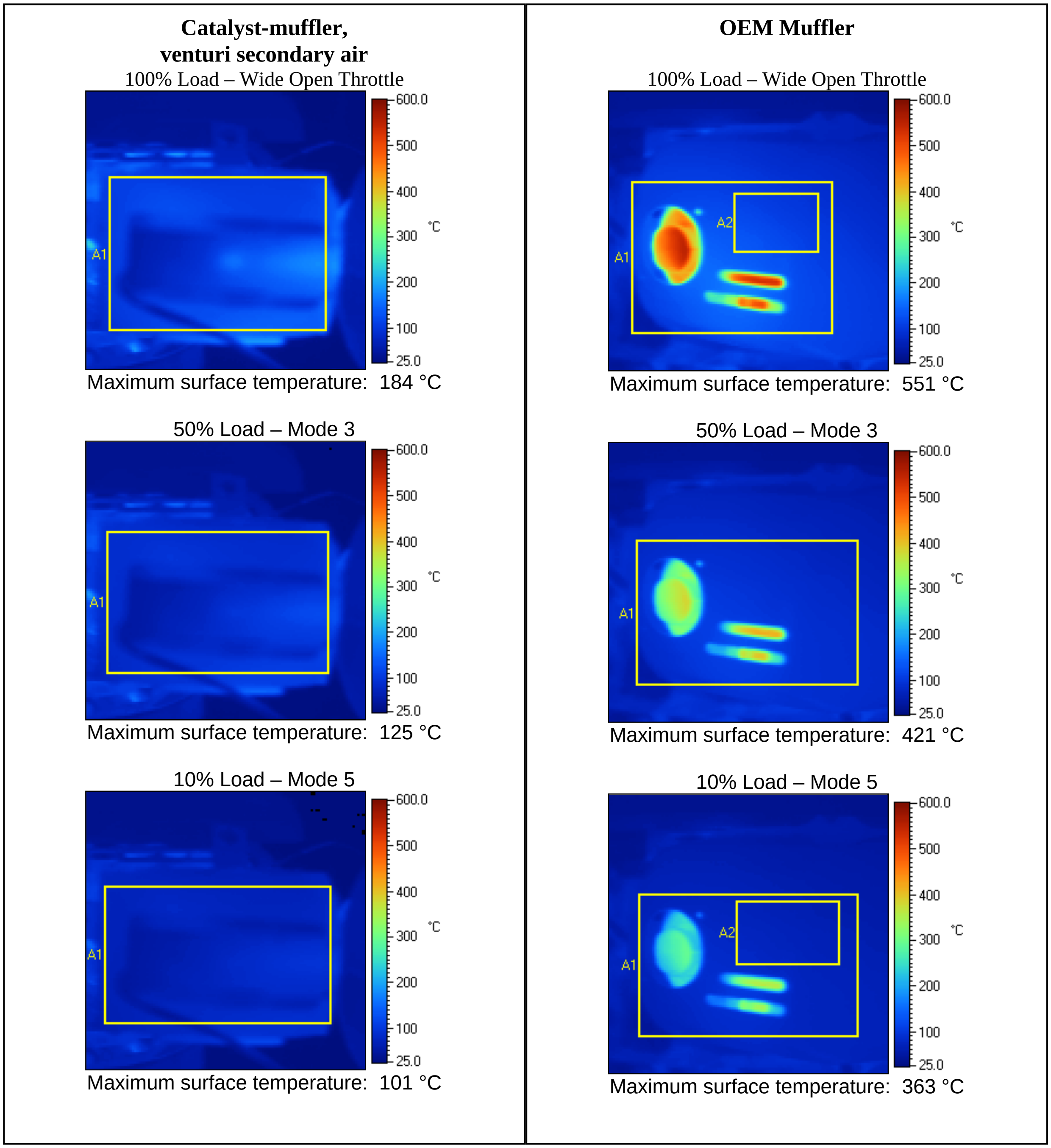


Figure 6-14: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 243 at high hours, equipped with a catalyst-muffler (left) compared to an engine from the same engine family (engine 244) equipped with an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle. In this case, the catalyst-muffler used a concentric tube venturi with an annular exhaust inlet. The OEM muffler configuration was equipped with a full shroud that directed air-flow over the muffler. This configuration was largely reproduced for the catalyst-muffler via modifications to the OEM shroud. An exhaust-ejector was also added for improved shroud and exhaust-gas cooling.

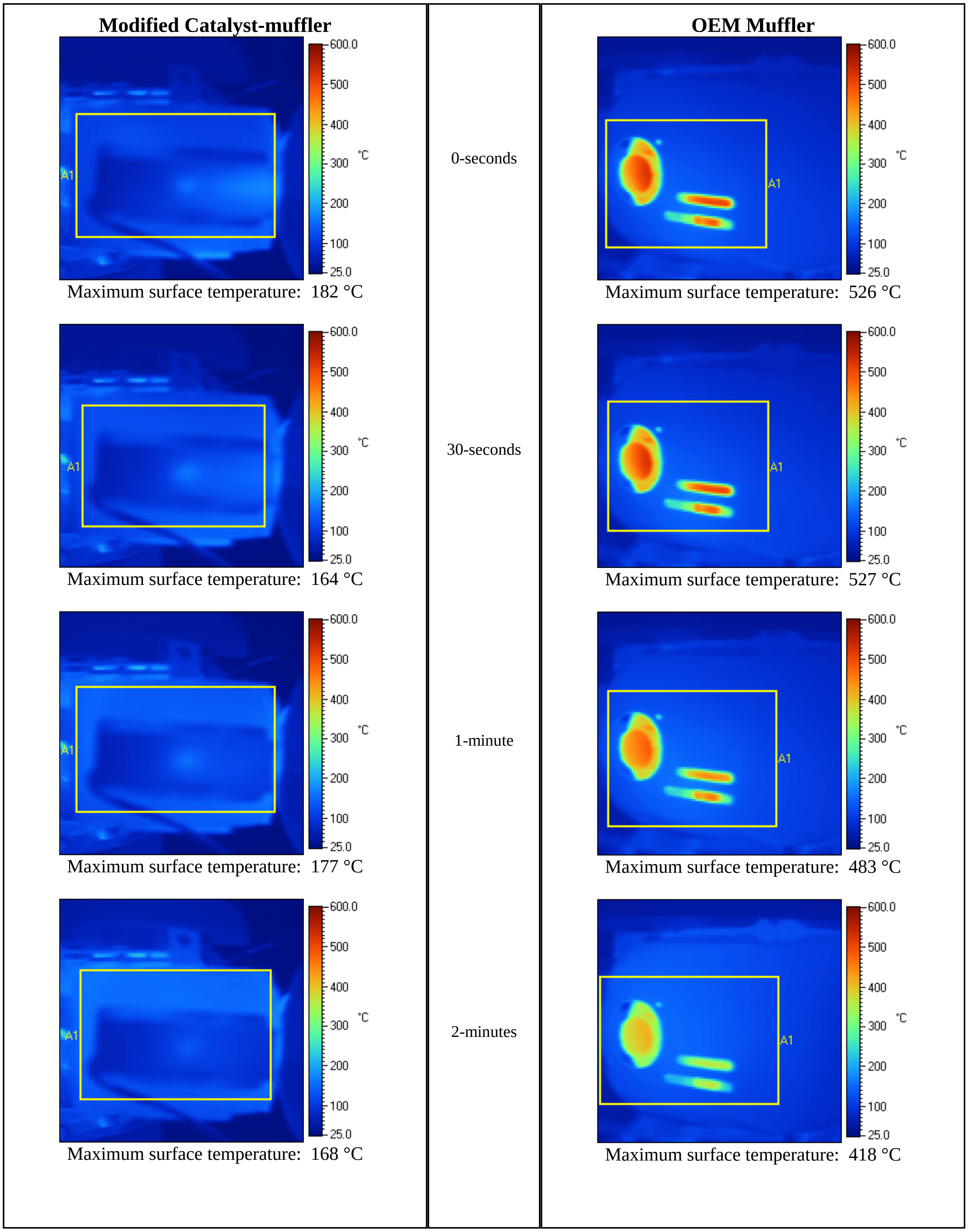


Figure 6-15: Infrared thermal images showing the surface temperatures of exhaust system components for engine 243 (left) and engine 244 (right) during a hot-soak period immediately after engine shutdown from sustained operation at WOT, 100% load (A-cycle mode 1).

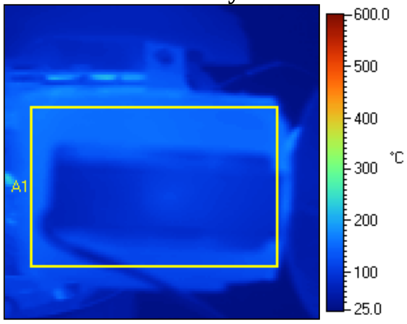
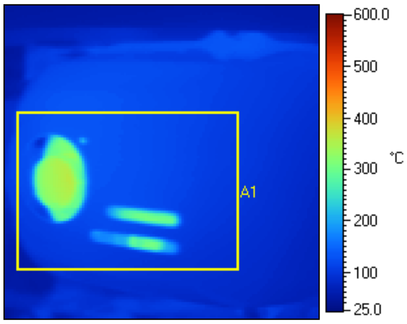
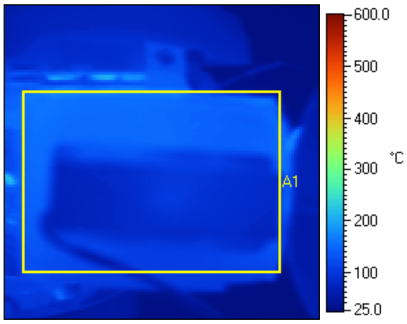
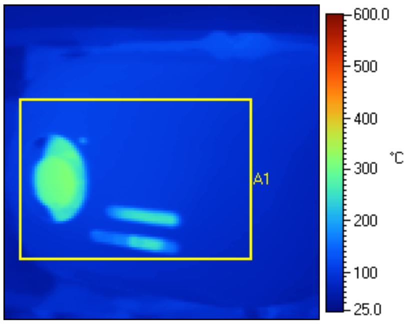
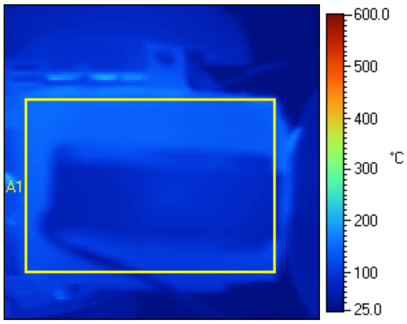
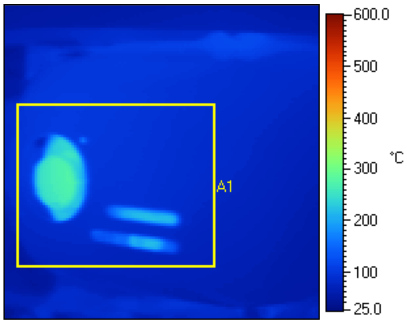
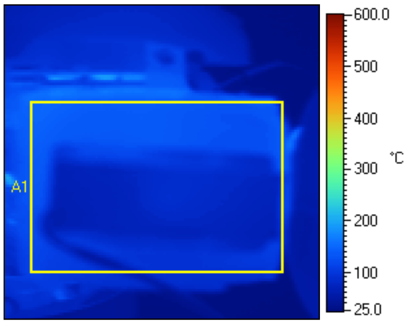
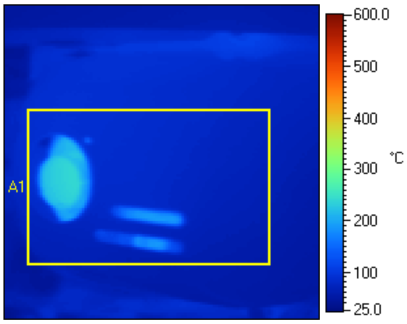
Modified Catalyst-muffler		OEM Muffler
 Maximum surface temperature: 168 °C	3-minutes	 Maximum surface temperature: 363 °C
 Maximum surface temperature: 183°C	4-minutes	 Maximum surface temperature: 319 °C
 Maximum surface temperature: 162 °C	5-minutes	 Maximum surface temperature: 280 °C
 Maximum surface temperature: 155 °C	6-minutes	 Maximum surface temperature: 248 °C

Figure 6-16: Continuation of the hot-soak shown in figure 6-15.

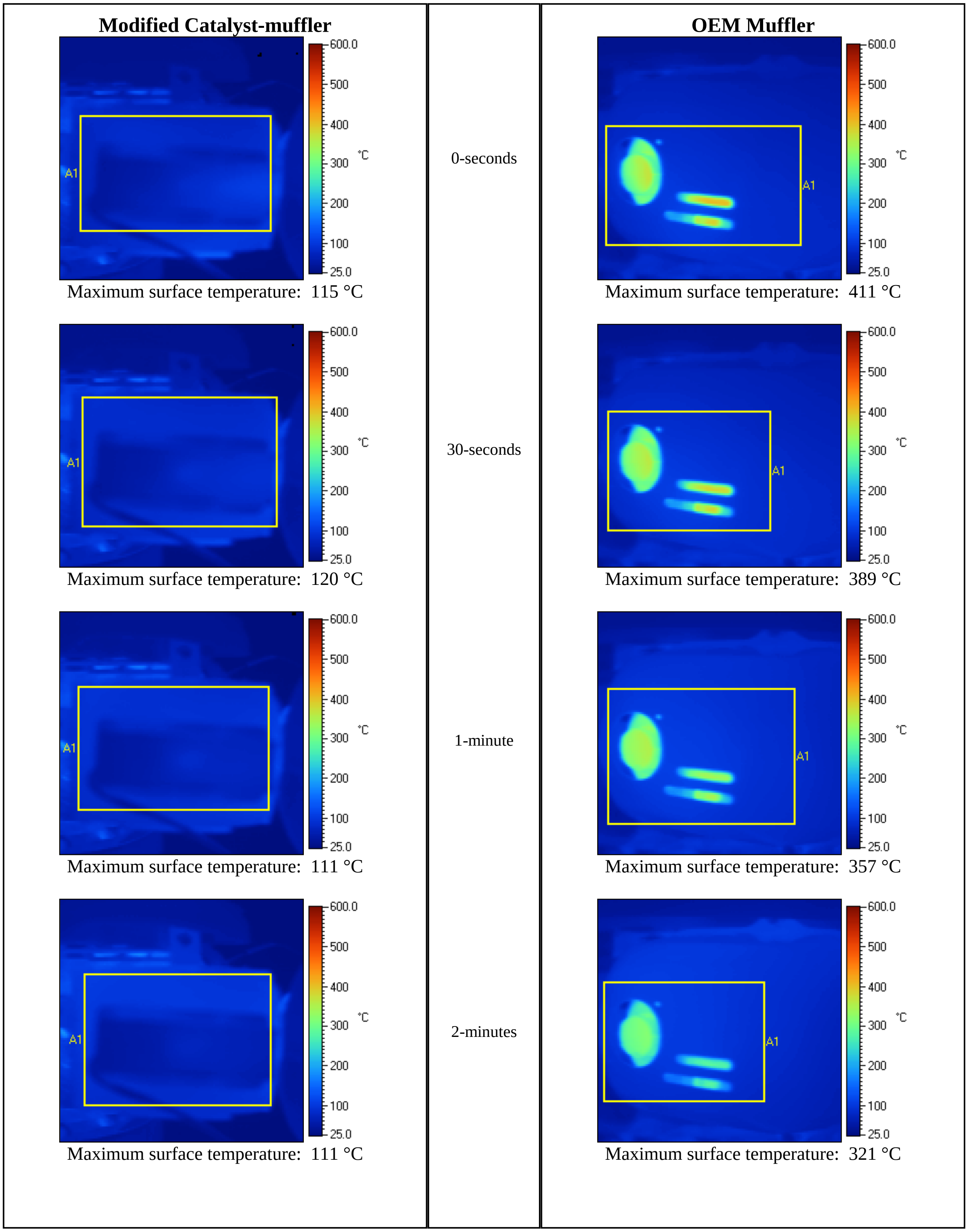
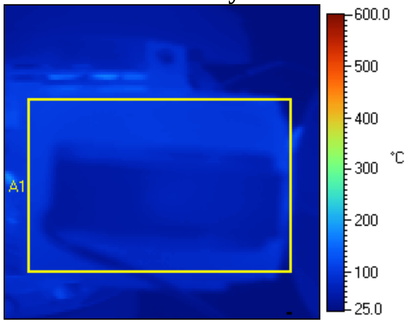


Figure 6-17: Infrared thermal images showing the surface temperatures of exhaust system components for engine 243 (left) and 244 (right) during a hot-soak period immediately after engine shutdown from sustained operation at 50% load (A-cycle mode 3).

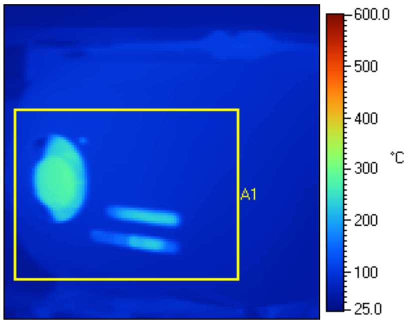
Modified Catalyst-muffler

OEM Muffler

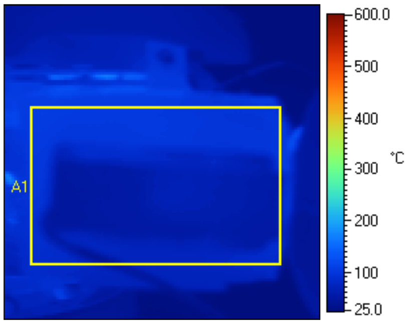


Maximum surface temperature: 132 °C

3-minutes

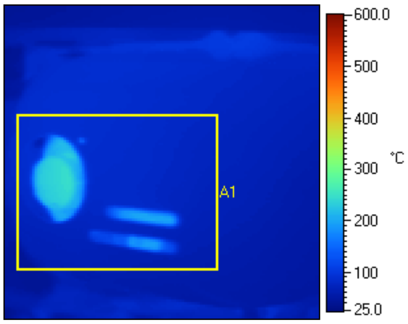


Maximum surface temperature: 284 °C

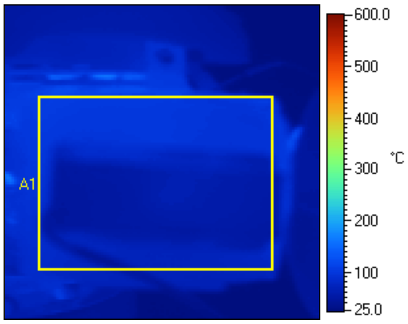


Maximum surface temperature: 112 °C

4-minutes

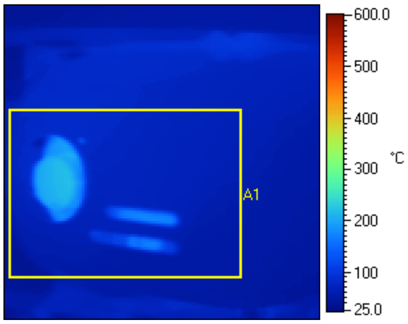


Maximum surface temperature: 251 °C



Maximum surface temperature: 113 °C

5-minutes



Maximum surface temperature: 224 °C

Figure 6-18: Continuation of the hot-soak shown in figure 6-17.

Infrared thermal imaging – Class II OHV Engines

Infrared thermal images are shown for three of the Class II lawn tractor engine types tested by EPA. It should be noted that the routing of cooling air through the lawn tractor chassis is important for both engine and exhaust system cooling. Also, for the catalyst-equipped configurations, the routing of cooling air through the chassis was modified to enhance cooling of exhaust system surfaces. Forced cooling of this type could not be adequately replicated during engine dynamometer testing, so the test results presented should be seen as worst case with respect to surface temperatures. Please refer to the field test results to see comparisons of engines and exhaust configurations as installed in the lawn tractor chassis.

Engine 231

Figure 6-19 shows infrared thermal images for A-cycle modes 1, 3 and 5 taken during laboratory testing of engine 231 equipped with a catalyst-muffler and EFI compared to an OEM configuration following approximately 10 hours of engine break-in and catalyst "degreening" and an additional 10 hours of operation accumulated during engine management system development. The catalyst-muffler used was similar to the one pictured in the lower right of figure 5-7. The peak temperatures for the catalyst-muffler were on the surfaces of the head-pipe and on the surfaces adjacent to a series of baffles located in the lower half of the muffler. The peak temperatures of the OEM muffler were on the surfaces of the head-pipe and on the upper half of the muffler, immediately upstream of the first muffler baffle. Comparable peak temperatures were found for both the catalyst-muffler and the OEM muffler for all six steady-state operating modes of the A-cycle. Surface temperatures for both configurations were approximately 100 °C higher than what was measured for the Class I configurations.

Engine 251

Figure 6-20 shows infrared thermal images for A-cycle modes 1, 3 and 5 taken during laboratory testing of engine 251 equipped with a catalyst-muffler and an OEM muffler. Engine 251 was from the same engine family as engine 231. The catalyst-muffler used was similar to the one shown in the middle-right of figure 5-7, but with the outlet on the bottom of the muffler. Peak surface temperatures for both the catalyst-muffler and the OEM muffler were on the head-pipe and the region of the muffler immediately downstream of the head-pipe. Comparable peak temperatures were found for both the catalyst-muffler and the OEM muffler for all six modes of the A-cycle.

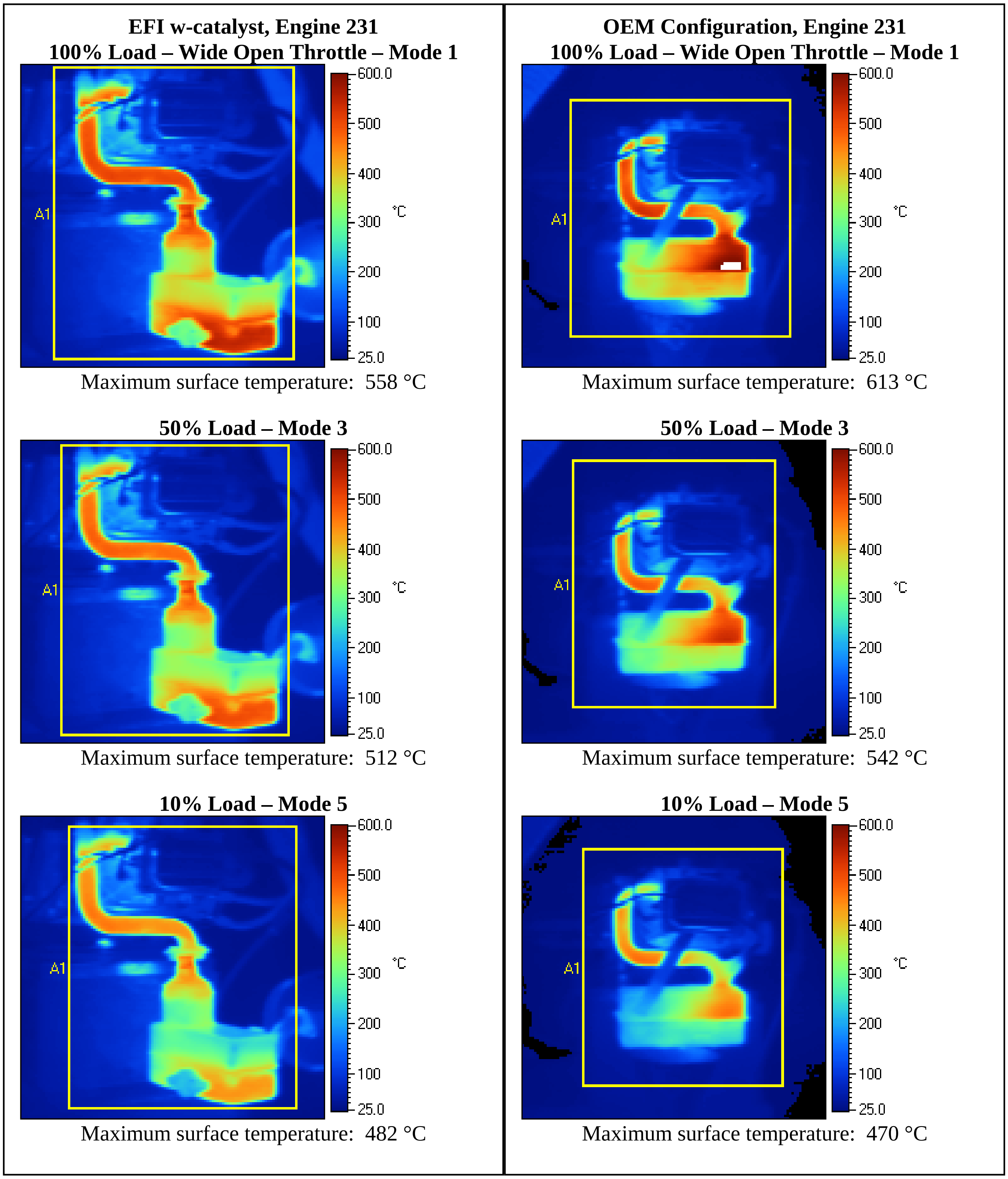
Hot soak tests were conducted with this engine from the 50% load condition (see figure 6-21 to 6-23). The cooling of the catalyst-muffler, as indicated by peak surface temperatures, lagged approximately one minute behind that of the OEM muffler, probably due to the increased mass of the catalyst-muffler in comparison with the OEM muffler. The time required for surface temperatures to cool to 250 °C was approximately six minutes for the catalyst-muffler and five minutes for the OEM muffler.

Engine 254

Figure 6-24 shows infrared thermal images for A-cycle modes 1, 3 and 5 taken during laboratory testing of engine 254 equipped with a catalyst-muffler and an OEM muffler. The catalyst-muffler used on engine 254 differed from the catalyst muffler used on engine 251 in several ways. The head-pipe used a double-wall construction to reduce its temperature. The overall substrate volume was reduced and divided into 2 parallel substrates to reduce exhaust back-pressure. Additionally, 100 cpsi metal-monolith construction was used instead of 200 cpsi, reducing cost and further reducing exhaust back-pressure. Peak temperatures were comparable between the catalyst-muffler and the OEM muffler systems for all six modes of the A-cycle. The double-wall construction reduced peak surface temperatures of the head-pipe used with the catalyst-muffler by approximately 150 °C at moderate to high-load conditions. Similar double-wall construction could also be applied to other parts of the exhaust system to reduce peak temperatures in specific locations.

During hot soak testing on engine 254 from sustained operation at WOT, cooling of the catalyst-muffler was comparable to the OEM muffler for the first 60 seconds, and then lagged behind the OEM system by one to two minutes for the remainder of the timed hot soak test (see Figures 6-25 to 6-27). During the hot-soak tests from the 50% load condition, the catalyst-muffler peak temperatures over the first 60 seconds cooled off faster than for the

OEM muffler. From approximately two minutes after shut-down to the end of the soak test, the cooling of catalyst-muffler peak surface temperatures lagged approximately one to two minutes behind those of the OEM muffler, similar to the WOT hot-soak conditions (see figures 6-28 and 6-29).



EFI w-catalyst, Engine 231
100% Load – Wide Open Throttle – Mode 1

Maximum surface temperature: 558 °C

50% Load – Mode 3

Maximum surface temperature: 512 °C

10% Load – Mode 5

Maximum surface temperature: 482 °C

OEM Configuration, Engine 231
100% Load – Wide Open Throttle – Mode 1

Maximum surface temperature: 613 °C

50% Load – Mode 3

Maximum surface temperature: 542 °C

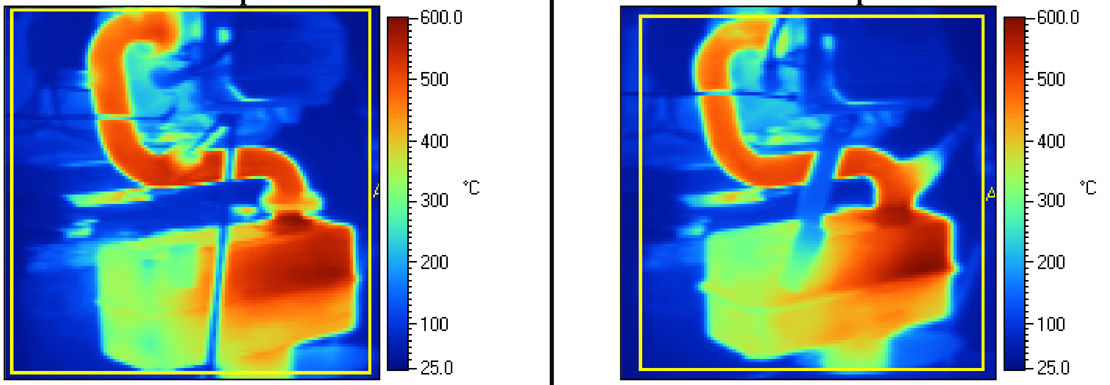
10% Load – Mode 5

Maximum surface temperature: 470 °C

Figure 6-19: Infrared thermal images showing the surface temperatures of exhaust system components for engine 231 at low hours, equipped with a open-loop EFI and a high-efficiency catalyst-muffler (left) and an OEM muffler (right).

OEM Carburetor w-catalyst, Engine 251
100% Load – Wide Open Throttle – Mode 1

OEM Configuration, Engine 251
100% Load – Wide Open Throttle – Mode 1

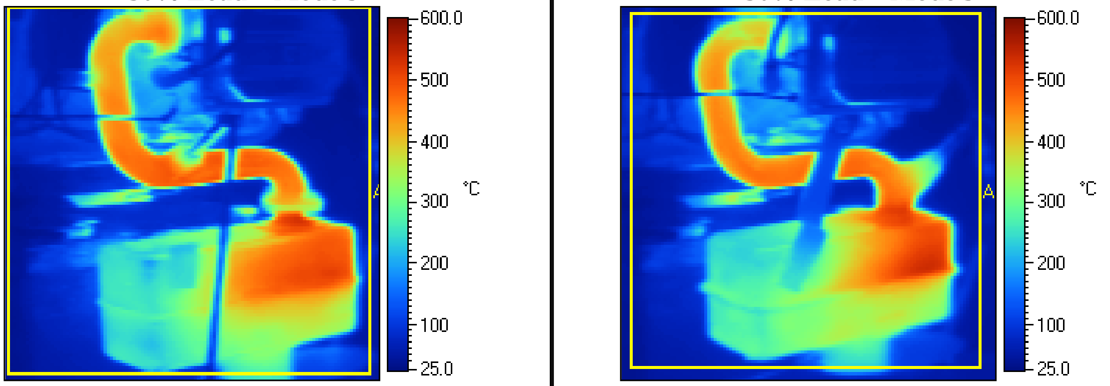


Maximum surface temperature: 591.7 °C

Maximum surface temperature: 599.3 °C

50% Load – Mode 3

50% Load – Mode 3

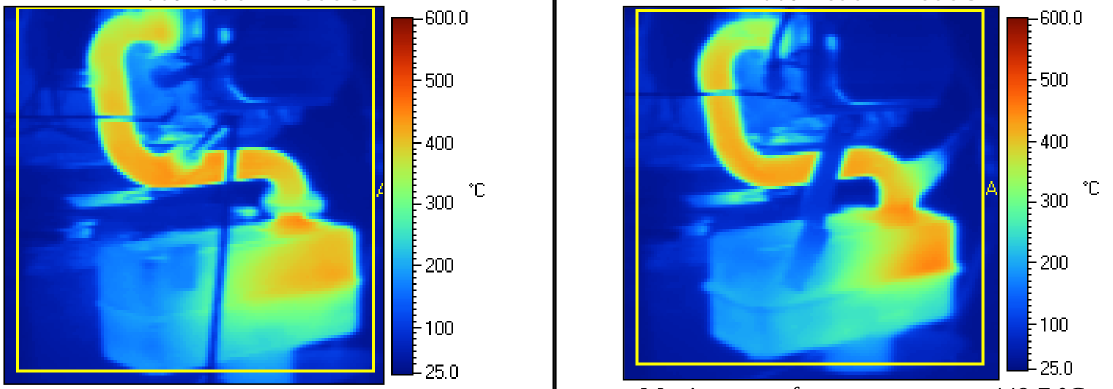


Maximum surface temperature: 529.7 °C

Maximum surface temperature: 538.9 °C

10% Load – Mode 5

10% Load – Mode 5



Maximum surface temperature: 445.5 °C

Maximum surface temperature: 449.7 °C

Figure 6-20: Infrared thermal images showing the surface temperatures of exhaust system components for engine 251 at low hours, equipped with catalyst-muffler (left) and an OEM muffler (right). Both configurations used the OEM carburetor.

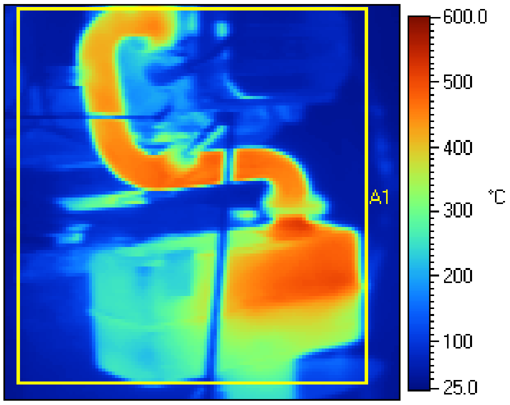
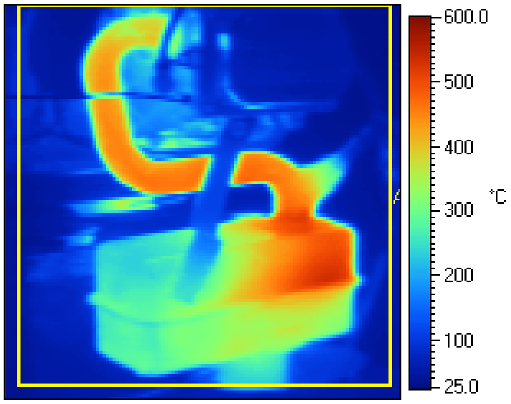
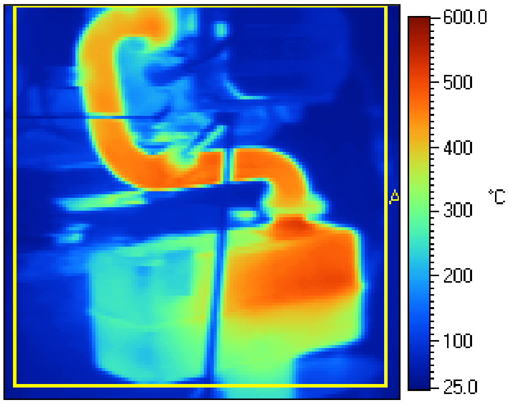
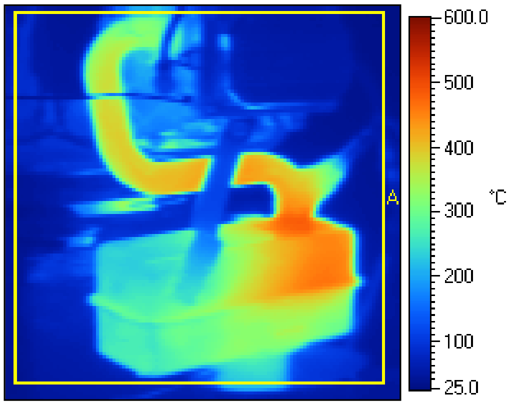
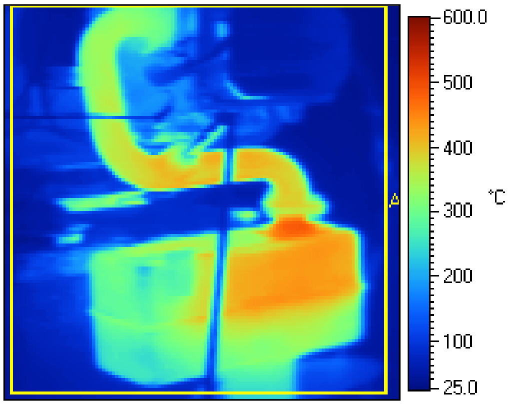
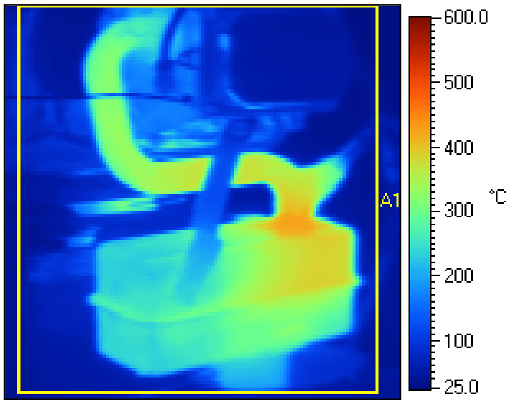
OEM Carburetor w-catalyst, Engine 251		**OEM Configuration, Engine 251**
 Maximum surface temperature: 520.4 °C	0-seconds	 Maximum surface temperature: 534.1 °C
 Maximum surface temperature: 521.1 °C	30-seconds	 Maximum surface temperature: 484.9 °C
 Maximum surface temperature: 489.4 °C	1-minute	 Maximum surface temperature: 430.0 °C

Figure 6-21: Infrared thermal images showing the surface temperatures of exhaust system components for engine 251 during a hot-soak period immediately after engine shutdown from sustained operation at 50% load (A-cycle mode 3).

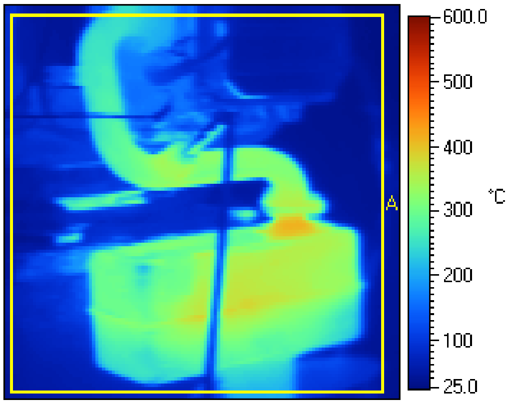
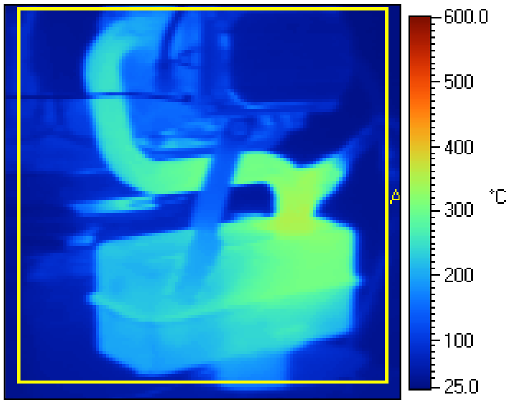
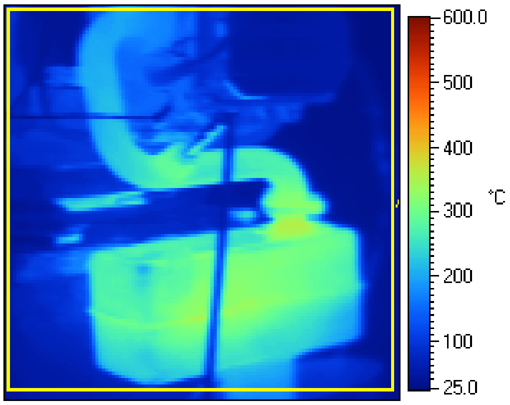
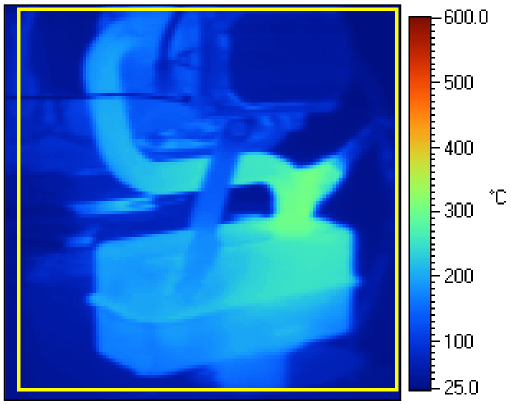
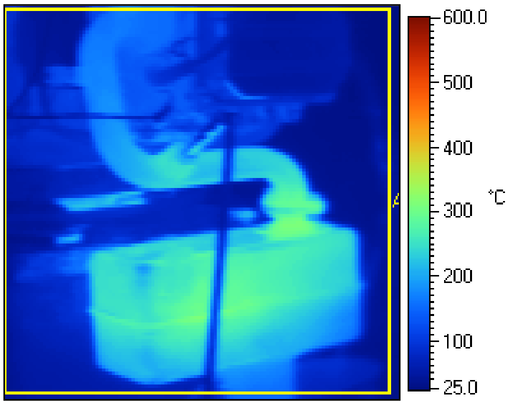
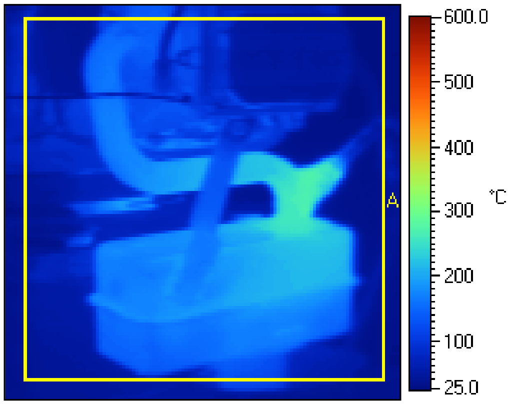
OEM Carburetor w-catalyst, Engine 251		**OEM Configuration, Engine 251**
 Maximum surface temperature: 415.7 °C	2-minutes	 Maximum surface temperature: 356.2 °C
 Maximum surface temperature: 358.7 °C	3-minutes	 Maximum surface temperature: 313.3 °C
 Maximum surface temperature: 316.6 °C	4-minutes	 Maximum surface temperature: 278.7 °C

Figure 6-22: Continuation of the hot-soak shown in figure 6-21.

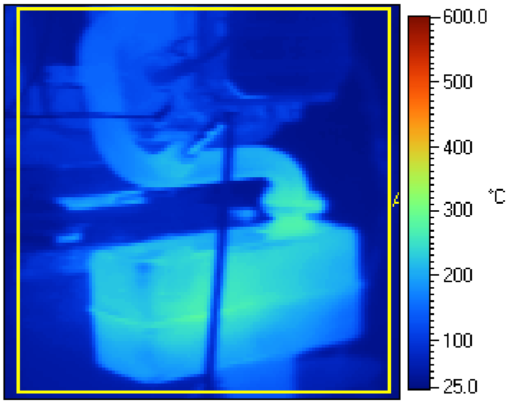
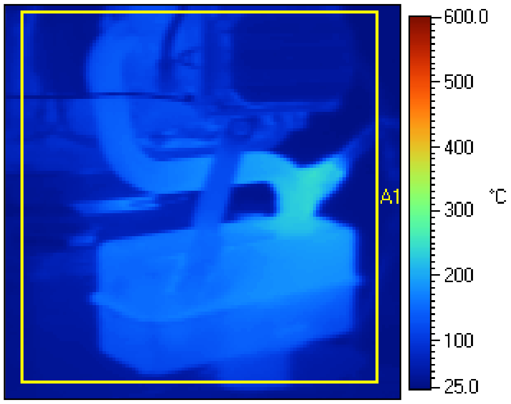
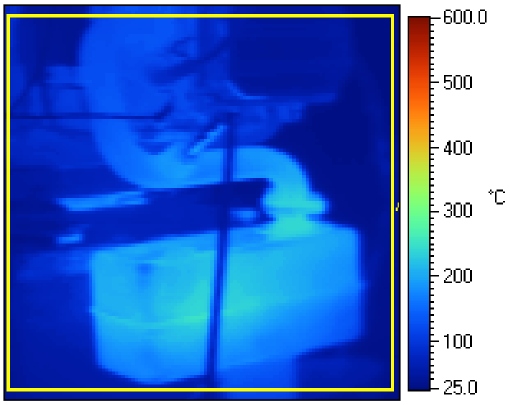
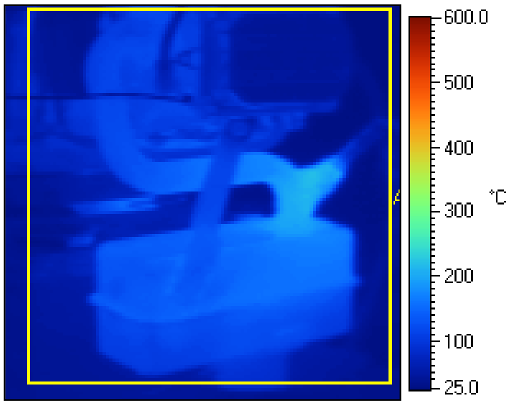
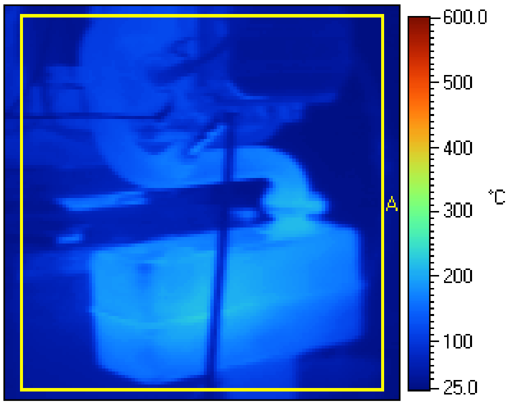
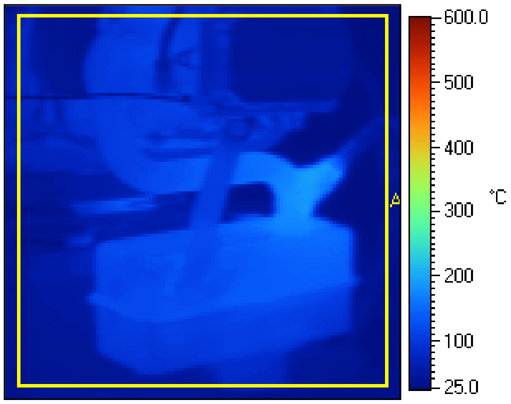
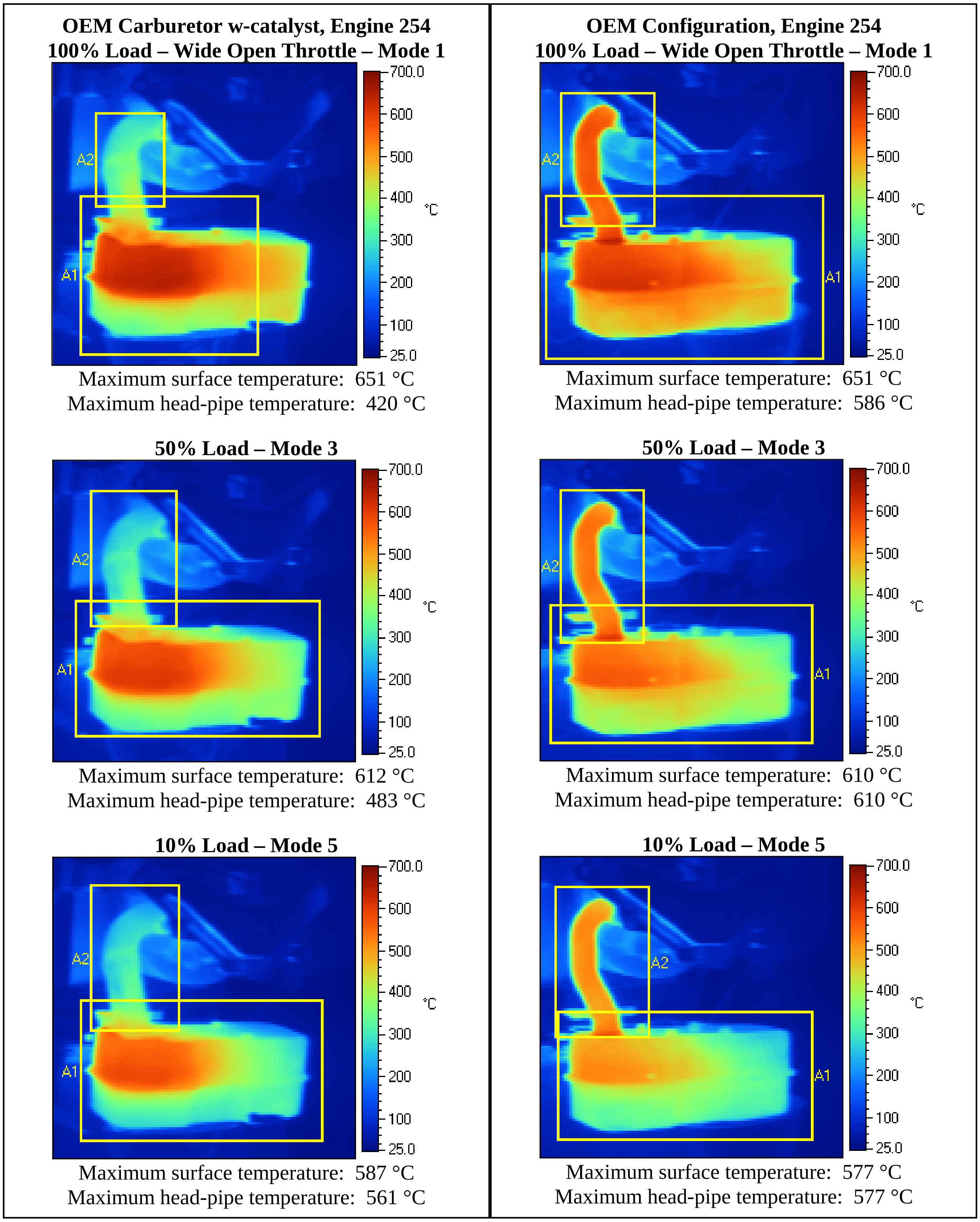
OEM Carburetor w-catalyst, Engine 251		**OEM Configuration, Engine 251**
 Maximum surface temperature: 286.3 °C	5-minutes	 Maximum surface temperature: 249.4 °C
 Maximum surface temperature: 258.2 °C	6-minutes	 Maximum surface temperature: 223.0 °C
 Maximum surface temperature: 234.5°C	7-minutes	 Maximum surface temperature: 201.8 °C

Figure 6-23: Continuation of the hot-soak shown in figures 6-21 and 6-22.



OEM Carburetor w-catalyst, Engine 254
100% Load – Wide Open Throttle – Mode 1

Maximum surface temperature: 651 °C
Maximum head-pipe temperature: 420 °C

50% Load – Mode 3

Maximum surface temperature: 612 °C
Maximum head-pipe temperature: 483 °C

10% Load – Mode 5

Maximum surface temperature: 587 °C
Maximum head-pipe temperature: 561 °C

OEM Configuration, Engine 254
100% Load – Wide Open Throttle – Mode 1

Maximum surface temperature: 651 °C
Maximum head-pipe temperature: 586 °C

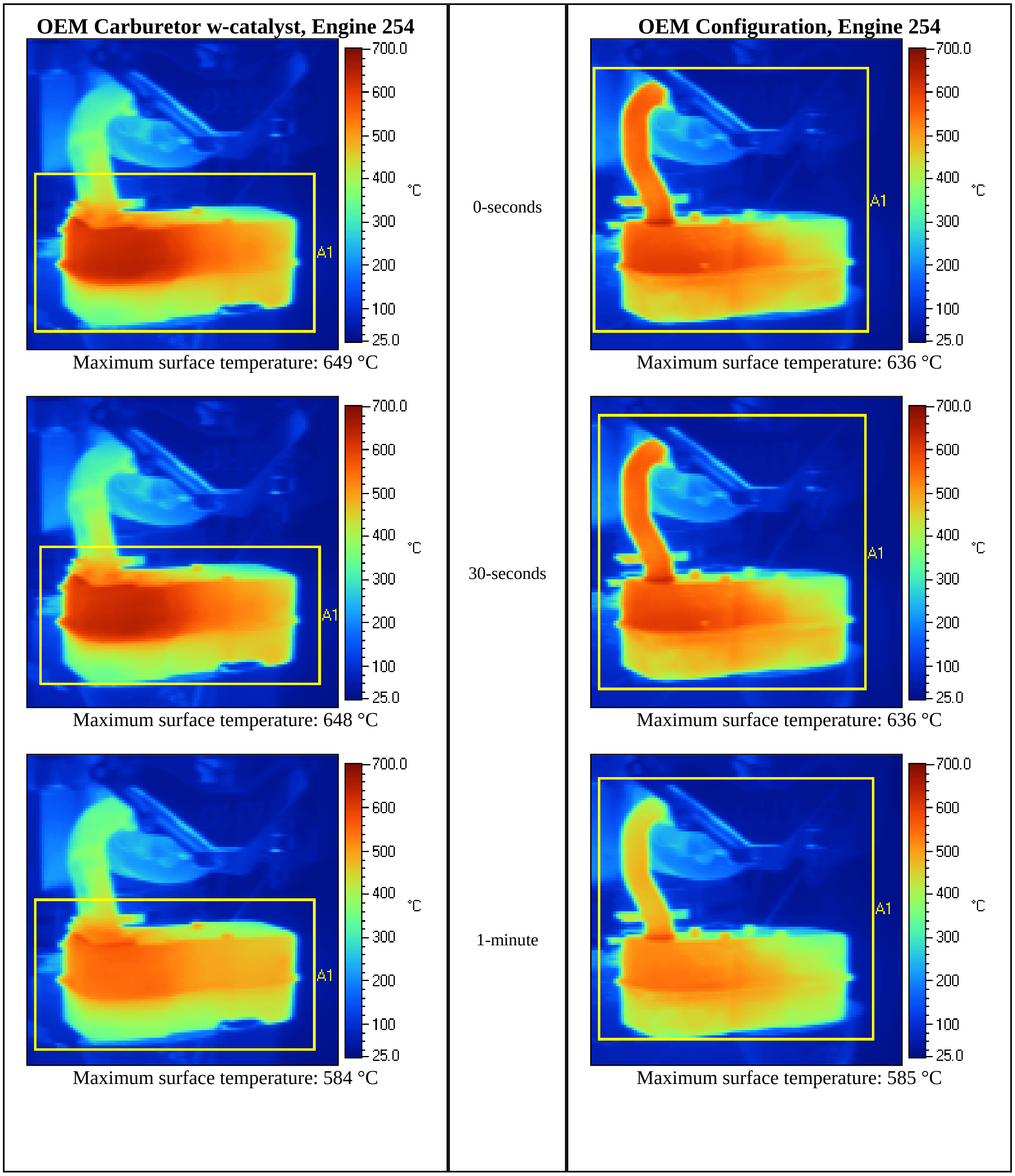
50% Load – Mode 3

Maximum surface temperature: 610 °C
Maximum head-pipe temperature: 610 °C

10% Load – Mode 5

Maximum surface temperature: 577 °C
Maximum head-pipe temperature: 577 °C

Figure 6-24: Infrared thermal images showing the surface temperatures of exhaust system components for engine 254 at low hours, equipped with catalyst-muffler (left) and an OEM muffler (right). Both configurations used the OEM carburetor.



OEM Carburetor w-catalyst, Engine 254

OEM Configuration, Engine 254

0-seconds

Maximum surface temperature: 649 °C

Maximum surface temperature: 636 °C

30-seconds

Maximum surface temperature: 648 °C

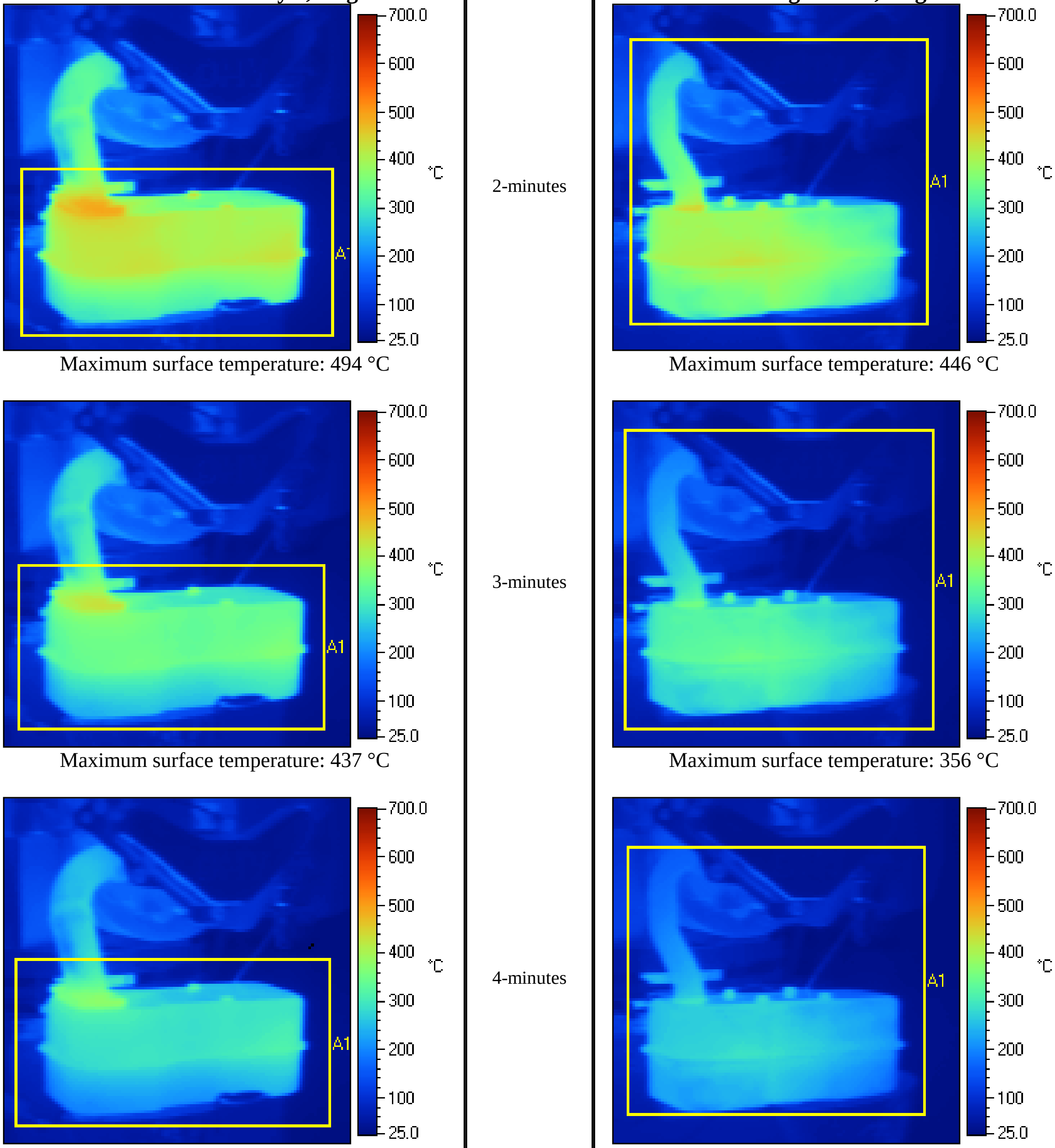
Maximum surface temperature: 636 °C

1-minute

Maximum surface temperature: 584 °C

Maximum surface temperature: 585 °C

6-25: Infrared thermal images showing the surface temperatures of exhaust system components for engine 254 during a hot-soak period immediately after engine shutdown from sustained operation at 100% load, WOT (A-cycle mode 1).



OEM Carburetor w-catalyst, Engine 254

OEM Configuration, Engine 254

2-minutes

Maximum surface temperature: 494 °C

Maximum surface temperature: 446 °C

3-minutes

Maximum surface temperature: 437 °C

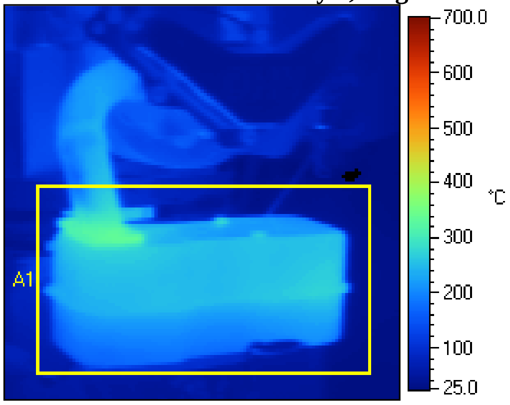
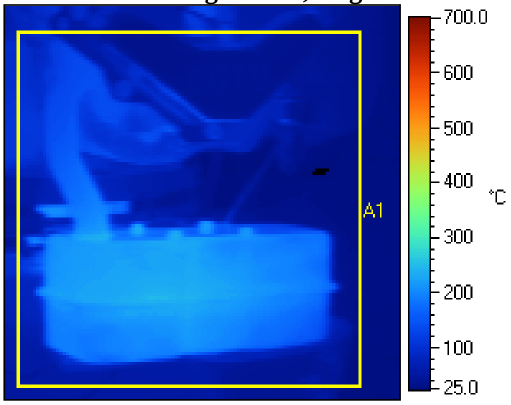
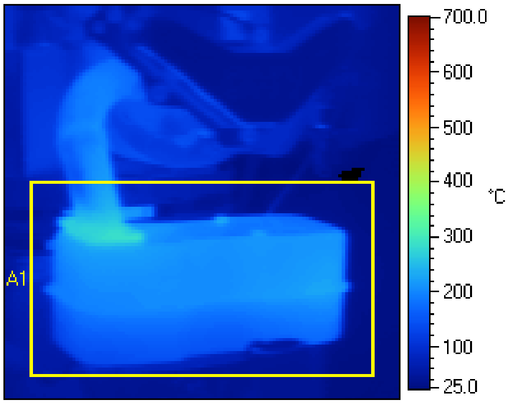
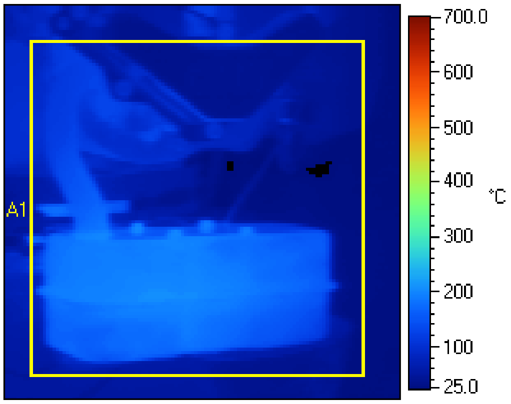
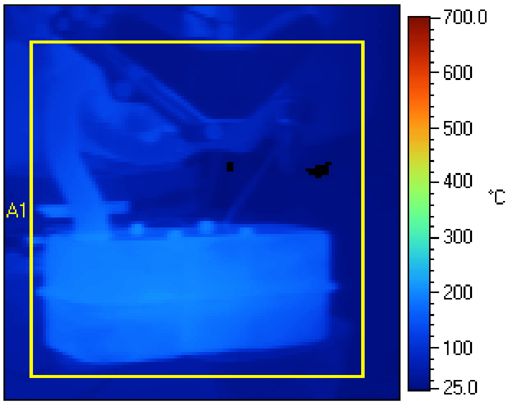
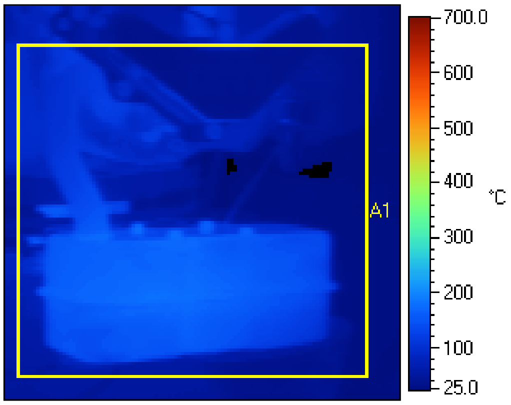
Maximum surface temperature: 356 °C

4-minutes

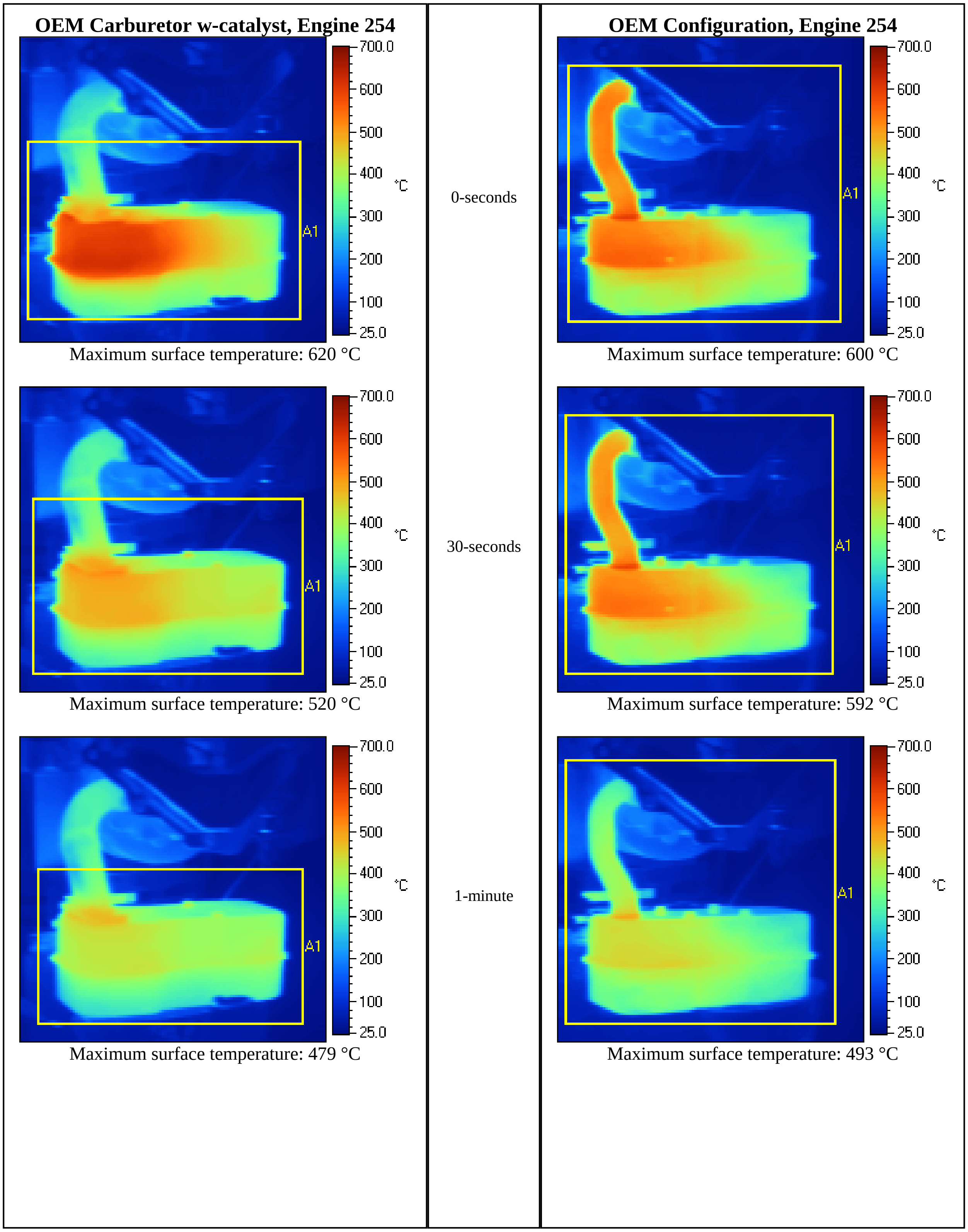
Maximum surface temperature: 384 °C

Maximum surface temperature: 298 °C

6-26: Continuation of the hot-soak shown in figure 6-25.

OEM Carburetor w-catalyst, Engine 254		**OEM Configuration, Engine 254**
 Maximum surface temperature: 340 °C	5-minutes	 Maximum surface temperature: 251 °C
 Maximum surface temperature: 292 °C	6-minutes	 Maximum surface temperature: 215 °C
 Maximum surface temperature: 260 °C	7-minutes	 Maximum surface temperature: 187 °C

6-27: Continuation of the hot-soak shown in figures 6-25 and 6-26.



OEM Carburetor w-catalyst, Engine 254

OEM Configuration, Engine 254

0-seconds

Maximum surface temperature: 620 °C

Maximum surface temperature: 600 °C

30-seconds

Maximum surface temperature: 520 °C

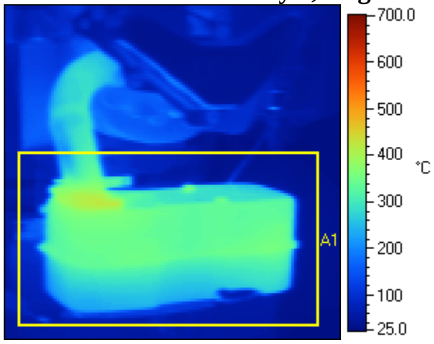
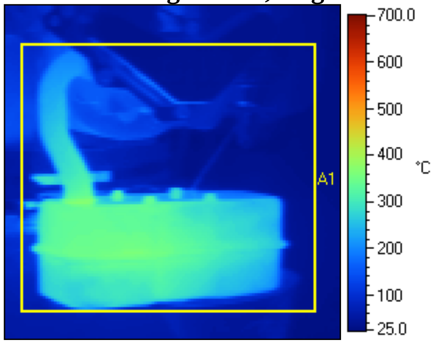
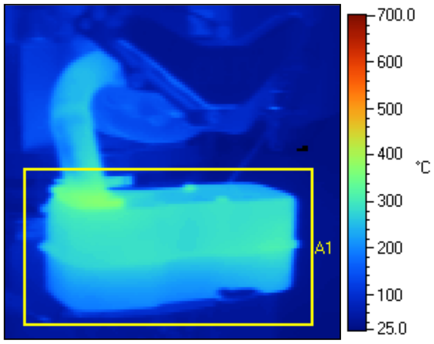
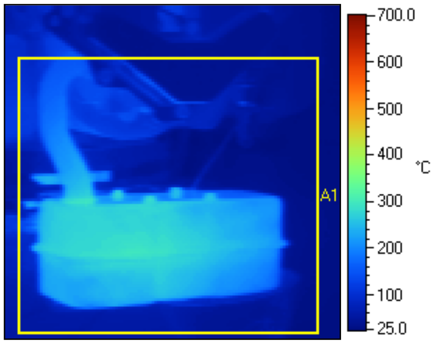
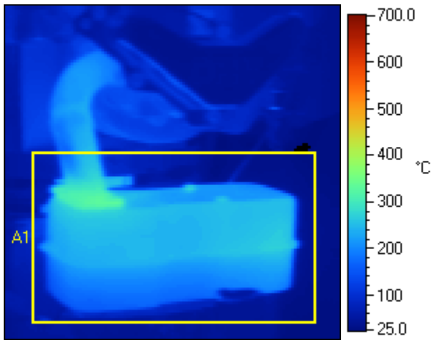
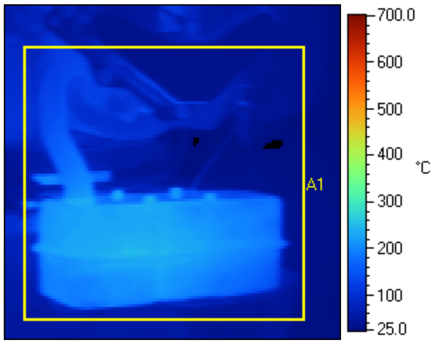
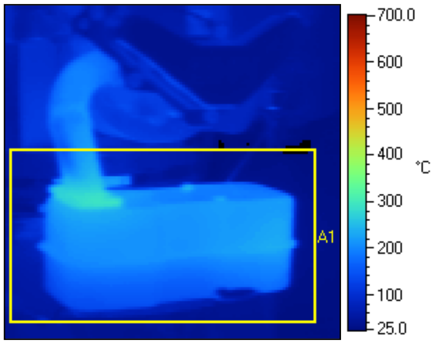
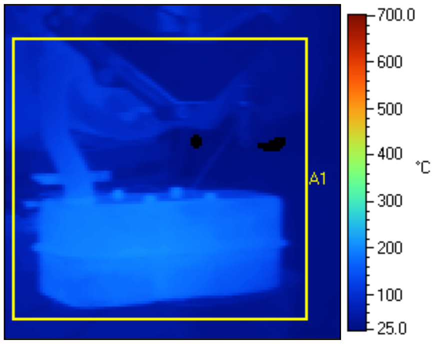
Maximum surface temperature: 592 °C

1-minute

Maximum surface temperature: 479 °C

Maximum surface temperature: 493 °C

6-28: Infrared thermal images showing the surface temperatures of exhaust system components for engine 254 during a hot-soak period immediately after engine shutdown from sustained operation at 50% load (A-cycle mode 3).

OEM Carburetor w-catalyst, Engine 254		**OEM Configuration, Engine 254**
 Maximum surface temperature: 424 °C	2-minutes	 Maximum surface temperature: 375 °C
 Maximum surface temperature: 375 °C	3-minutes	 Maximum surface temperature: 302 °C
 Maximum surface temperature: 334 °C	4-minutes	 Maximum surface temperature: 254 °C
 Maximum surface temperature: 298 °C	5-minutes	 Maximum surface temperature: 215 °C

6-29: Continuation of the hot-soak shown in figure 6-28.

Muffler outlet temperatures – Class I and Class II Engines

Exhaust gas outlet temperatures measured for each of the 6-modes of the A-cycle tests are shown in Figure 6-30 for representative examples of Class I side-valve, Class I OHV, and Class II OHV engine for both OEM muffler and catalyst-muffler configurations. The exhaust outlet temperatures for the Class I catalyst-mufflers were comparable or cooler in comparison with the Class I OEM mufflers. The Class II catalyst-muffler exhaust outlet temperatures were 30-40 °C higher than the OEM muffler. When mounted in the lawn tractor chassis, all of the Class II engines tested in the field were equipped with exhaust ejectors that significantly lowered the exhaust gas temperatures at the outlet via mixing with ambient air.

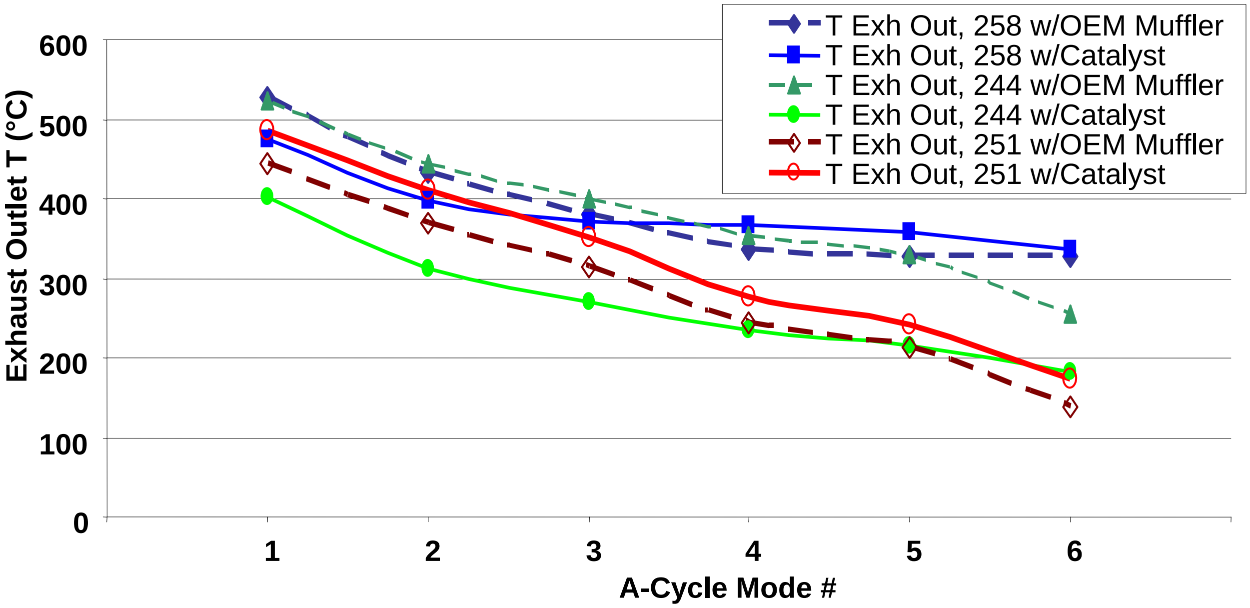


Figure 6-30: Exhaust gas outlet temperatures measured during engine dynamometer testing over the 6 steady-state modes of the A-cycle test for representative Class I side-valve (258) and OHV (244) engines and for a Class II engine (251). Note that the dashed lines are for OEM muffler configurations, and the solid lines are for catalyst-muffler configurations.

Run-on after-fire testing

A digital image from one of the tests is presented in Figure 6-31. A full comparison of the OEM muffler and the catalyst-muffler configurations tested under the same test conditions will require viewing of digital video acquired during testing. Digital video files may be accessed for viewing via the Phase 3 Nonroad SI Engine Docket and also from the DVD attached to this study.[1] The test conditions are described in Chapter 5.

After-fire was evident for engine 241 for each of the four tests of the high-inertia shut-down conditions tested with the OEM muffler. This can be seen quite dramatically in digital videos. In many cases, a flash of flame exited the tailpipe during after-fire (Figure 6-31). In all cases, a series of a sharp "bangs" in the audio track of the videos are evident, sounding similar to a fire-cracker. The force of the after-fire can be seen in the resulting recoil of the exhaust collection cone mounted downstream of the tailpipe. It should be noted that the collection cone was mounted to an approximately 25-lb base located approximately 3 feet below the collection cone.

The tests were repeated four times with the catalyst-muffler, but after-fire was not evident for the four repeats of the high-inertia shut-down conditions. While the catalyst muffler was adapted from an OEM design, the two-stage inner baffling differed somewhat in its physical layout (a 3/4" diameter perforated tube followed by a perforated plate, with 0.125" perforations) and surface area to prevent flame propagation. A degree of flow restriction was also added near the muffler exit through the use of a serviceable OEM spark arresting screen.

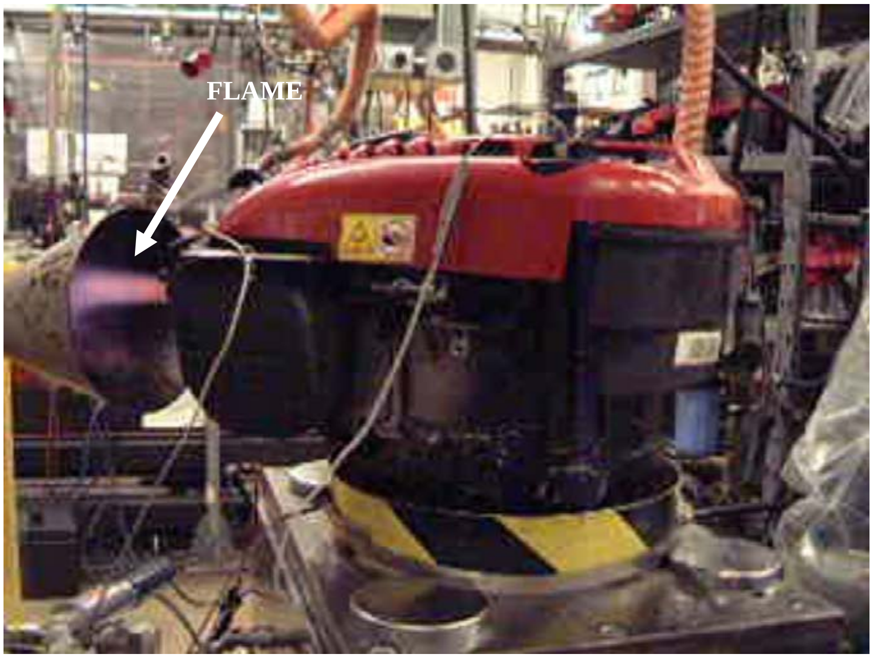


Figure 6-31: Digital image taken of engine 241 during after-fire testing with OEM muffler. A 6” or longer after-fire flame was observed extending from the tailpipe into the exhaust collection cone, accompanied by a sharp “bang” similar to a firecracker. Repeated testing of engine 241 under the same conditions with a catalyst-muffler did not result in after-fire.

Ignition misfire testing

Audible engine misfire, increased engine vibration, and erratic torque output were observed while operating engine 255 at the 25% misfire condition. The misfire condition is clearly visible within the torque, speed, and HC data (see Figures 6-32 and 6-33) and in digital video taken of engine operation during misfire. Digital video files showing engine operation during operation at the 25% misfire condition may be accessed for viewing within the Phase 3 Nonroad SI Docket and from the DVD attached to this study[1].

Infrared thermal images comparing the tested catalyst-muffler and OEM muffler configurations are presented in Figures 6-34 and 6-35. The peak temperatures of the catalyst-muffler were approximately 60 °C cooler than the OEM muffler prior to the onset of ignition misfire. After 30 seconds of operation at 25% random ignition misfire, the OEM muffler peak temperatures were unchanged and the catalyst-muffler peak temperatures had increased to approximately the same temperature as the OEM muffler. As misfire progressed, the OEM muffler began to cool and the catalyst muffler temperatures continued to increase. Temperatures for both configurations stabilized between three and five minutes of operation. After five minutes of misfire, the catalyst-muffler had approximately 130 °C higher peak surface temperatures than the OEM muffler at the same condition (see Figure 6-34). The stabilized temperatures of the catalyst-muffler undergoing 25% random misfire were comparable to the OEM muffler operating normally at a 50% load condition (Figure 6-8). The temperature increase was due to the exothermic reaction of partially burned fuel components over the catalyst substrate. The catalyst-muffler used with engine 255 included a number of design elements to limit the exothermic reaction during misfire. These included dividing the catalyst volume upstream and downstream of the secondary, reducing the amount of secondary air, and choosing a formulation for the upstream pre-catalyst that favored net-rich HC reactions appeared. The design appeared to be moderately successful at limiting the exotherm since peak temperatures stabilized to less than 400 °C after approximately three minutes of misfire.

Additional testing was conducted to determine if air-shrouding similar to that used with engines 243 and 244 would be effective at reducing the peak temperatures of exposed surfaces to temperatures below the corresponding peak temperatures obtained with the OEM muffler configuration (see Figure 6-35). With the shroud in place, peak temperatures during misfire testing were reduced substantially, and remained at least 50 °C cooler than the OEM configuration. Peak temperatures of the shrouded catalyst muffler were relatively constant throughout the five minutes of misfire. The surface temperature of the shroud adjacent to location of the catalyst within the exhaust system and the surface temperature of the exhaust ejector outlet increased from approximately 100 °C prior to the onset of misfire to stabilized temperatures of approximately 180 °C after five minutes of ignition misfire.

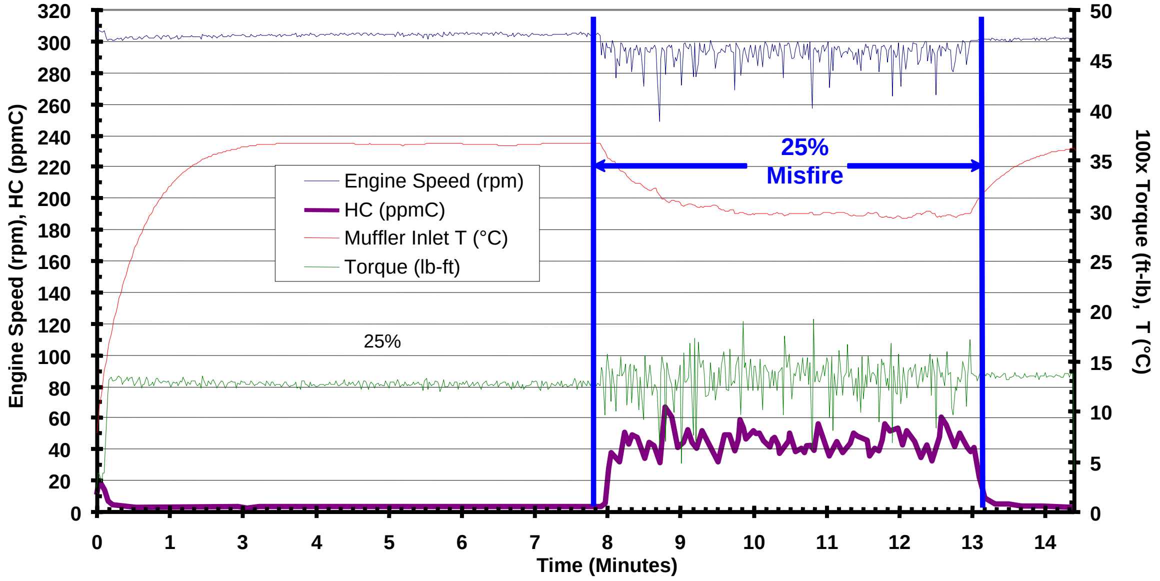


Figure 6-32: Operational data with engine 255 and OEM muffler showing initial temperature stabilization followed by approximately five minutes of operation with 25% random ignition misfire. Note that HC concentrations are from dilute-CVS measurements.

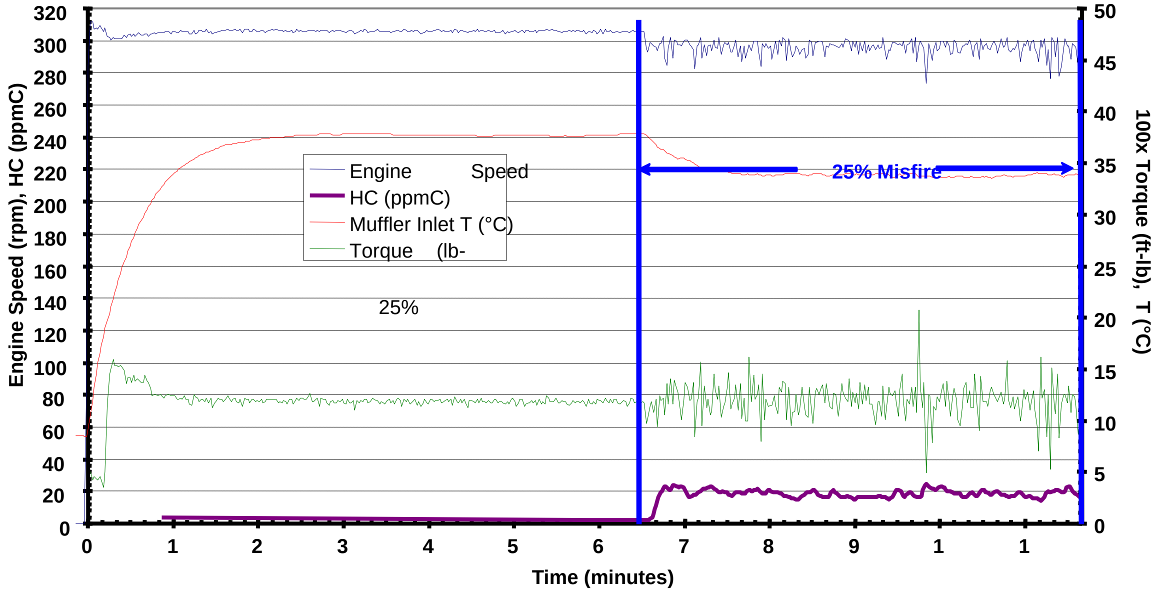
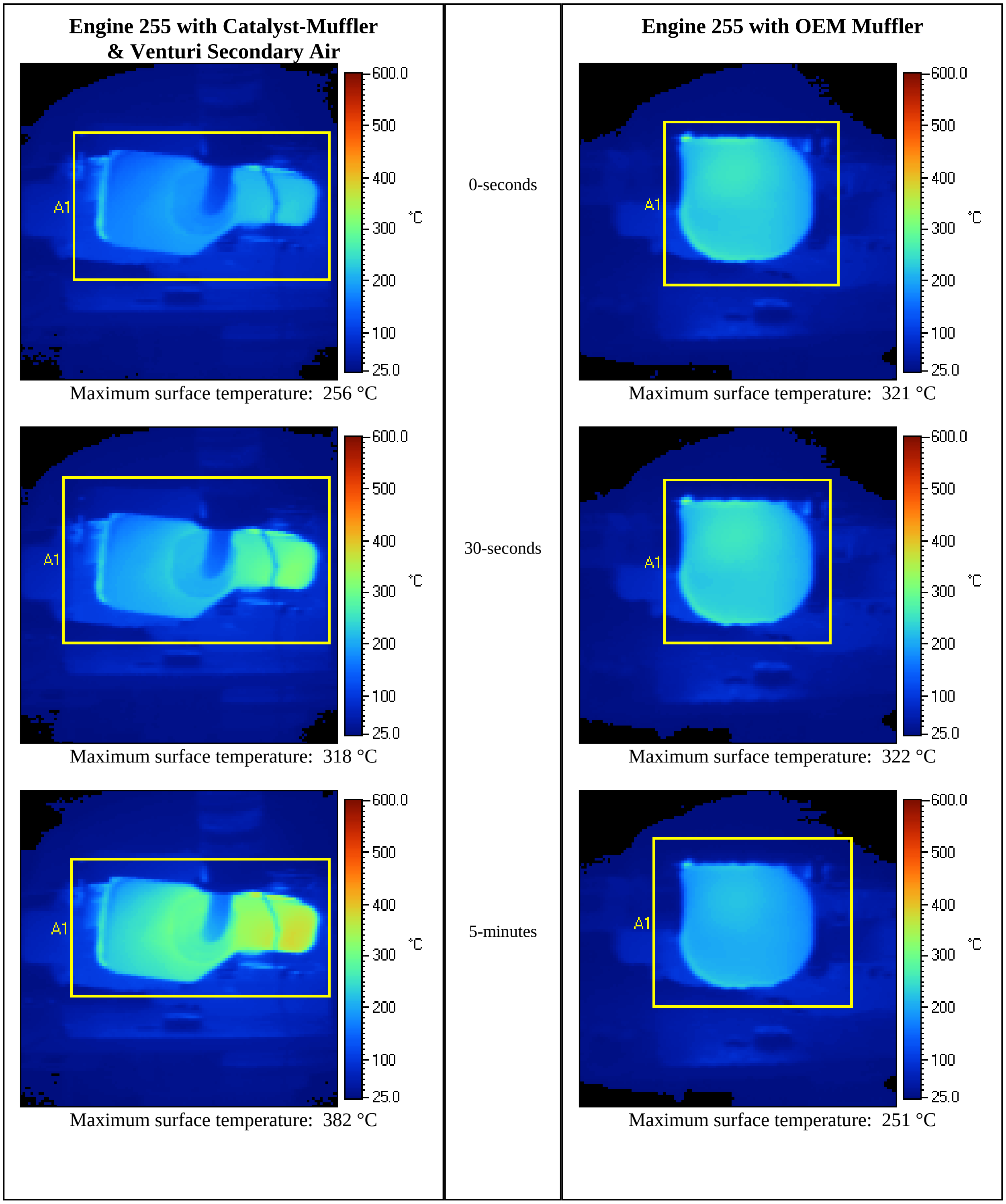


Figure 6-33: Operational data with engine 255 and catalyst-muffler showing initial temperature stabilization followed by approximately five minutes of operation with 25% random ignition misfire. Note that HC concentrations are from dilute-CVS measurements.



Engine 255 with Catalyst-Muffler & Venturi Secondary Air

Engine 255 with OEM Muffler

0-seconds

Maximum surface temperature: 256 °C

Maximum surface temperature: 321 °C

30-seconds

Maximum surface temperature: 318 °C

Maximum surface temperature: 322 °C

5-minutes

Maximum surface temperature: 382 °C

Maximum surface temperature: 251 °C

Figure 6-34: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 255 at low hours equipped with a catalyst-muffler (left) and an OEM muffler (right). The images were taken immediately before (top) and after 30 seconds (middle) and five minutes (bottom) of continuous operation at a condition of 25% random misfire and the minimum torque measured for the lawn mower blade for this application at 2900 rpm (approximately 25% load or A-cycle mode 4).

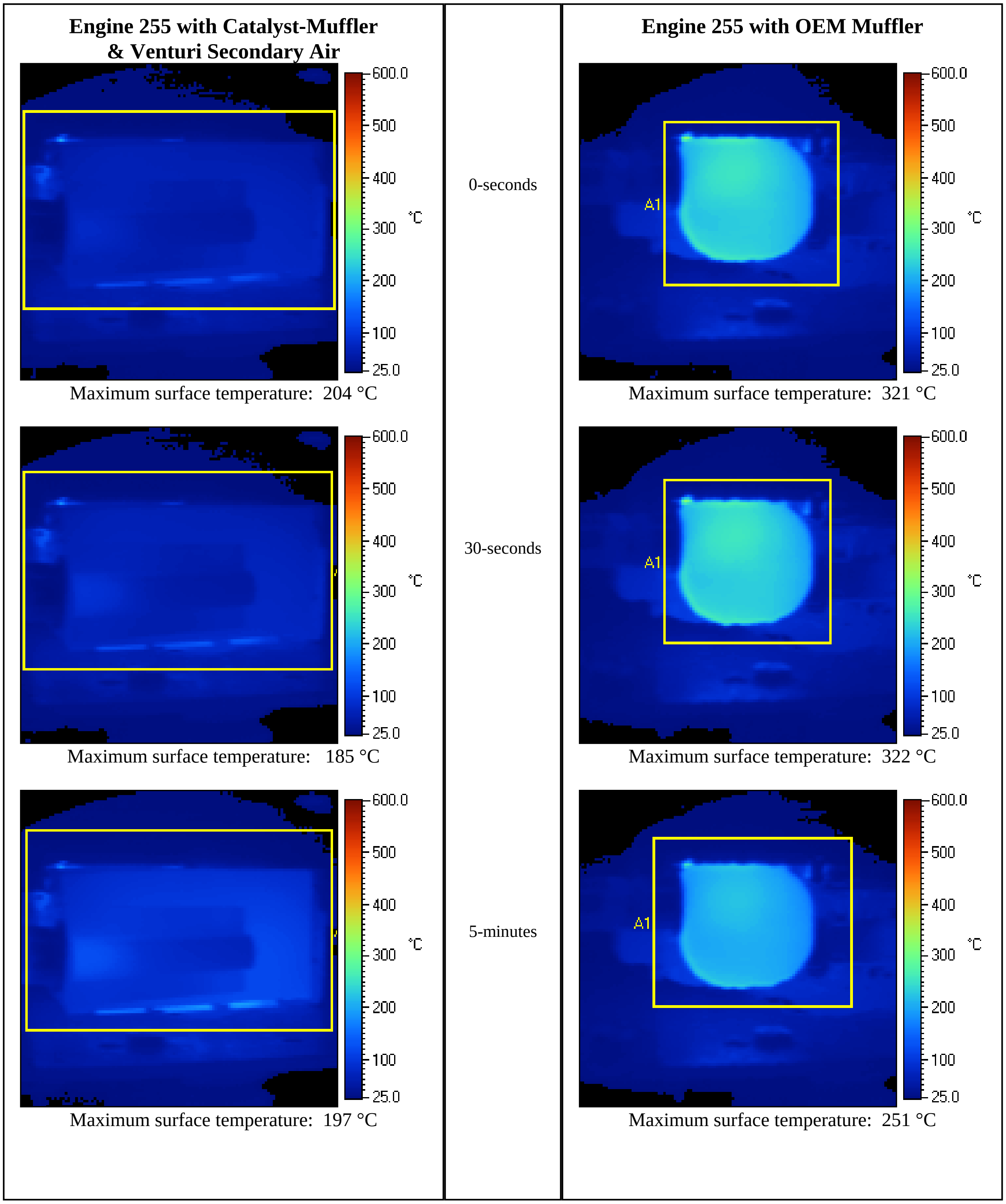


Figure 6-35: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 255 at low hours equipped with a catalyst-muffler and air shroud (left) and an OEM muffler (right). The images were taken immediately before (top) and after 30 seconds (middle) and five minutes (bottom) of continuous operation at a condition of 25% random misfire and the minimum torque measured for the lawn mower blade for this application at 2900 rpm (approximately 25% load or A-cycle mode 4).

Rich Operation

The 1.0 to 1.5 change in air-to-fuel ratio was achievable for A-cycle modes 1-4 via changes to the main carburetor jet. During mode 5, the main jet change resulted in a change of 0.7 air-to-fuel ratio, and no change for mode 6. Figure 6-36 shows a comparison between the air-to-fuel ratio achieved with the OEM carburetor main jet and the modified carburetor on engine 255. Engine-out CO emissions increased in modes 1 to 4 of the A-cycle by approximately 40 to 50%. Engine-out HC emission were approximately doubled. Power at WOT increased by approximately 6%.

Thermal imaging results for operation over modes 1, 3 and 5 of the A-cycle are shown in 6-36. Peak surface temperatures were comparable between the catalyst-muffler and OEM configurations over all six modes of the A-cycle. Surface temperatures for the catalyst muffler were virtually unchanged relative to the tests conducted with the OEM carburetor jetting. Although higher concentrations of CO and HC reactants were available in the exhaust, the richer operation also limited the amount of oxygen available in the exhaust, which limited the exothermic oxidation reactions of the CO and HC over the catalyst. The richer carburetor jetting reduced the peak surface temperatures of the OEM muffler by approximately 30 to 40 °C, or to approximately the same peak temperatures as those of the catalyst-muffler.

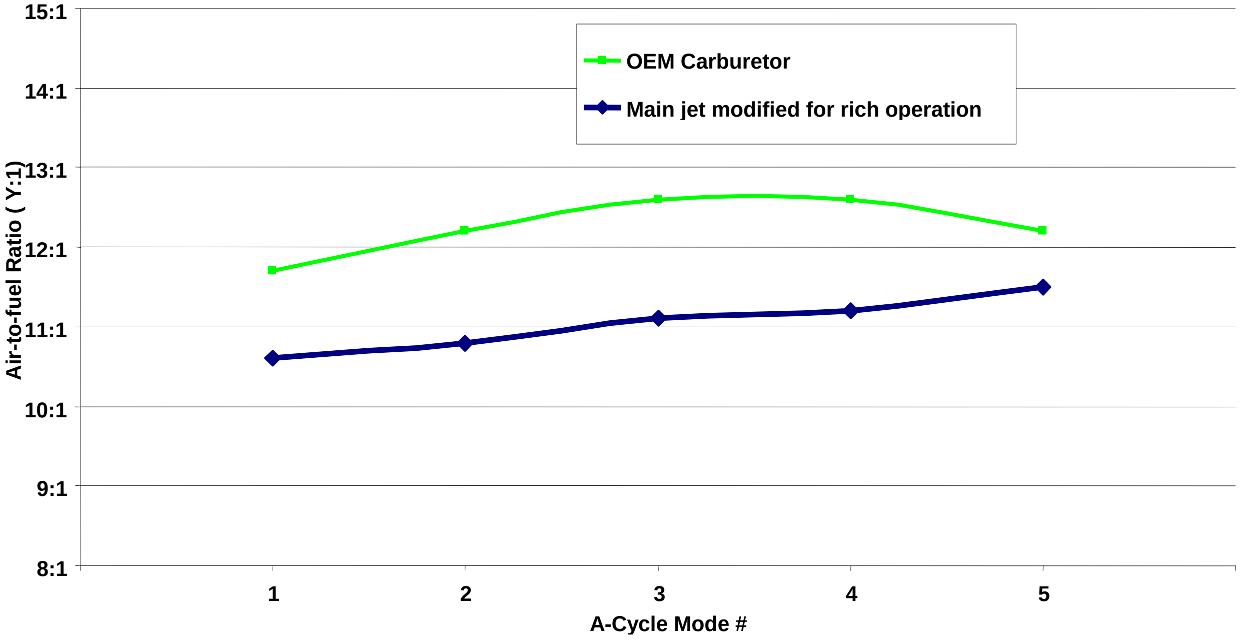
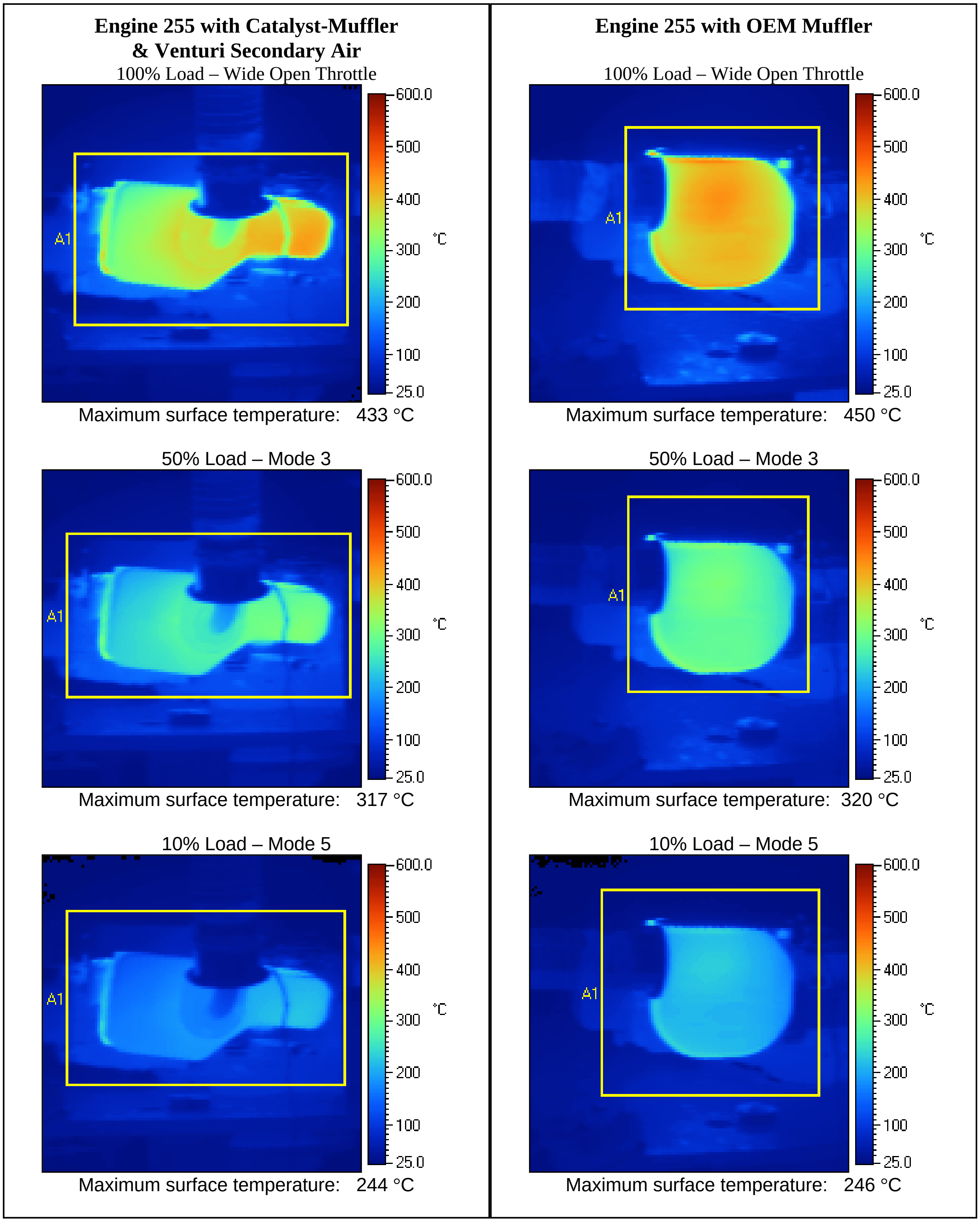


Figure 6-36: A comparison of air-to-fuel ratio for the first five modes of the A-cycle test.



Engine 255 with Catalyst-Muffler & Venturi Secondary Air

100% Load – Wide Open Throttle

Maximum surface temperature: 433 °C

50% Load – Mode 3

Maximum surface temperature: 317 °C

10% Load – Mode 5

Maximum surface temperature: 244 °C

Engine 255 with OEM Muffler

100% Load – Wide Open Throttle

Maximum surface temperature: 450 °C

50% Load – Mode 3

Maximum surface temperature: 320 °C

10% Load – Mode 5

Maximum surface temperature: 246 °C

Figure 6-37: Infrared thermal images showing the surface temperatures of exhaust system components for OHV engine 255 at low hours equipped with a catalyst-muffler (left) and an OEM muffler (right) for modes 1, 3 and 5 of the A-cycle with the carburetor main-jet modified to provide 1-1.5 richer air-to-fuel ratio than the OEM jetting.

C. FIELD TESTING RESULTS

During the course of field testing, over 1200 individual refueling events were carried out on six walk-behind lawn mowers and four lawn tractors without incident. Of these, four of the lawn mowers and two of the lawn tractors were equipped with catalyst-mufflers and accounted for over 700 of the refueling events. Auxiliary fuel cans were kept in close proximity to grass cutting operations and thus refueling typically occurred less than two minutes after engine shut-down.

During field operations in Tennessee, four of the lawn mowers (all with the same engine type) had unacceptable levels of debris accumulation in the area of the engine cooling shroud immediately above the cylinder head and on top of the engine cylinder and required frequent maintenance. The issue was related to the design of the cooling fan and the fan air-intake and caused maintenance issues with both the OEM and catalyst-equipped configurations of this engine family. The other two engines from a different engine family that were used during field testing (244, 245) did not have any appreciable debris accumulation within the OEM engine shroud. These two engines used a small perforated screen attached to the top of the cooling fan to prevent debris above a certain size from entering the cooling fan and engine shroud. Engines 244 and 245 also used a cooling fan with significantly higher flow (30 curved fan vanes versus six flat-paddle type vanes). Engines 246, 248, and 249 were retrofitted with screens near the inlet to the cooling fan and no further debris accumulation problems were encountered (see Figure 6-38).

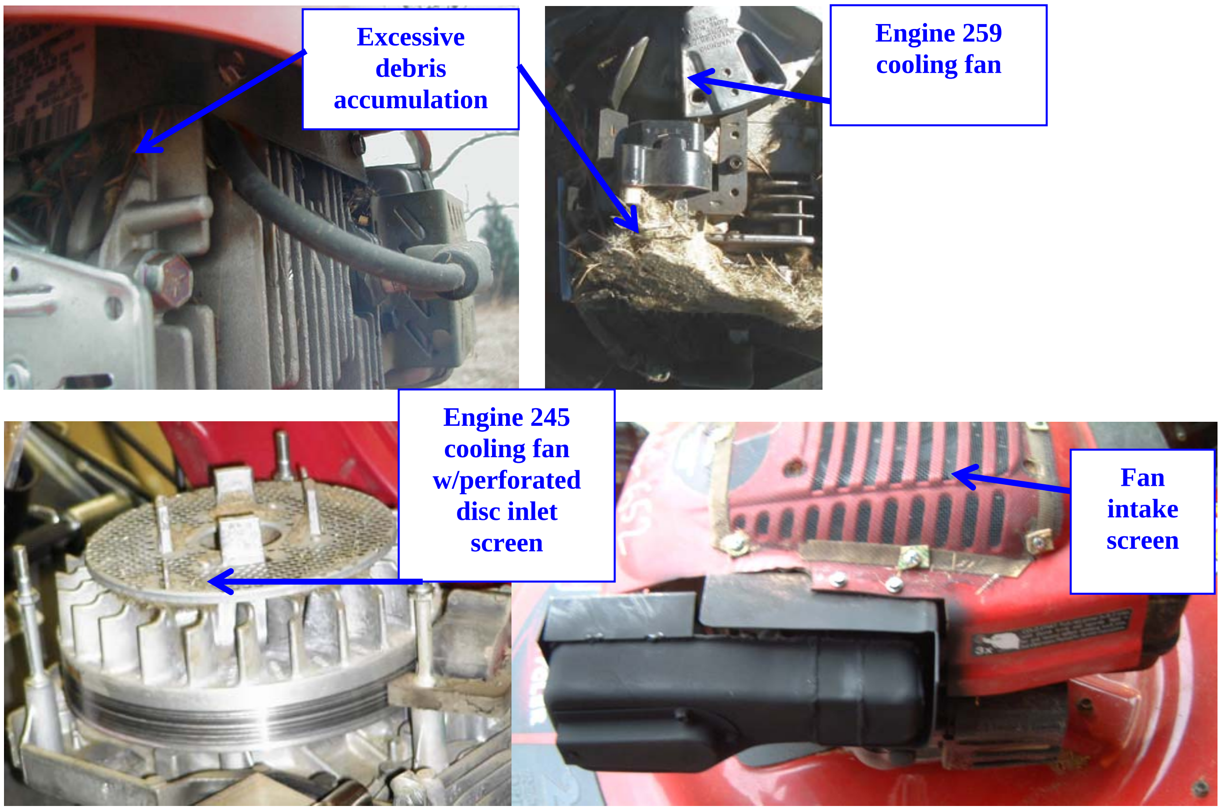


Figure 6-38: Engines 246, 248, 249 and 259 had problems with excessive debris build-up underneath the engine cooling shroud (top, engine 259 shown). Engine 245 had negligible debris build-up on engine and catalyst-muffler surfaces, even after 110 hours of field operation (bottom left). Note the perforated disc attached to the top of the cooling fan that prevented debris ingestion with engine 245. An exterrnal screen was added near engine fan's air-intake on engines 246, 248 and 249 to eliminate ingestion of large debris by the engine cooling fan (bottom right).

During hundreds of hours of grass cutting operations there was no discernable difference in operation attributable to the use of catalyst-mufflers with the lawn mowers or the lawn tractors. All of the lawn mowers were operated to approximately 100 to 110 hours (within 15-25 hours of the end of useful life). The lawn tractors were operated to approximately 240 hours (within 10 hours of the end of useful life for engines 231 and 252 and to within 10 hours of mid-life for engines 232 and 233).

<u>Surface Temperature Measurements by Infrared Thermal Imaging Taken During Grass Cutting Operations</u>

Full motion video infrared thermal images were used to allow surface temperature measurement with the equipment under load during grass cutting operations. Observations drawn from the videos will be presented in this section. A full comparison of IR video images from the OEM muffler and the catalyst-muffler configurations tested during field operations will require viewing of digital video data acquired during testing. Digital video files may be accessed for viewing via the Phase 3 Nonroad SI Engine Docket and also via the DVD attached to this study.[1] The IR thermal images were acquired at ambient conditions of 18.5 °C (65 °F), 80% relative humidity and little to no wind for the testing in Tenneessee. The IR thermal images were acquired at ambient conditions of 30 °C (86 °F) , 46% relative humidity with light 5 to 10 mph winds. The impact of the wind was not readily apparent in the surface temperature measurements from the equipment, but effect of wind can clearly be seen on the turf surfaces for the IR video images taken during idling. The grass cutting conditions can be seen in Figures 5-14 and 5-15.

Class I Lawn Mowers

The lawn mower equipped with engine 259 and an OEM muffler was operating with surface temperatures exceeding 360 °C during cutting of moderate to heavy grass. The lawn mowers equipped with engines 244 and 245 and catalyst-mufflers were operating with surface temperatures of approximately 120 °C and 150 °C, respectively, during grass cutting in approximately the same location. The lawn mowers equipped with engines 246 and 248 and catalyst mufflers operated with surface temperatures of approximately 280 °C. The lawn mower equipped with engine 249 and a catalyst-muffler operated with surface temperatures of approximately 130 °C. In all cases, the surface temperatures of the lawn mowers equipped with catalyst-muffler configurations were significantly less than the lawn mower equipped with engine 259 and the OEM muffler. The sub-200 °C temperatures achieved with engines 244, 245, and 249 are due to the use of air shrouding and forced-air cooling around the muffler and due to the use of ejector cooling of the exhaust gases and the outer surface of the air shroud. The lower surface temperatures of the catalyst-mufflers used with engine 244 and 249 relative to that used with engine 245 may have been due to the reduced use of platinum within their catalyst washcoating formulations. Engine 249 used a rhodium-only formulation and engine 244 used a formulation that was predominantly palladium with a small amount of platinum and rhodium. The best combination of emissions control and lower surface temperatures for these applications appeared to be achievable using a trimetallic washcoating formulation of approximately 30 g/ft^3 – 40 g/ft^3 PGM that were predominantly palladium with smaller, roughly equivalent amounts of platinum and rhodium. The rhodium-only catalyst was also comparably effective at achieving low surface temperatures and was capable of similar emission control performance to the palladium-rich trimetallic formulations at much lower loading levels (i.e., only slightly higher total PGM cost). The rhodium-only catalyst was also the only catalyst in this testing capable of reaching EPA’s HC+NOx emission targets without the use of passive secondary air. The lack of secondary air and reduced CO oxidation for engine 249 may have also contributed to its relatively low surface temperatures during grass cutting.

Class II Lawn Tractors – 3.5 g/kW-hr systems

The lawn tractor equipped with engine 252, which was an OEM muffler and induction system configuration, had exposed surface temperatures of approximately 150 °C as viewed from both sides of the tractor when cutting moderate to heavy grass. Note that the view of the exhaust outlet of the muffler was obscured by the OEM touch guard over the exhaust system. The lawn tractor equipped with engine 231, which had the EFI system and catalyst-muffler, had exposed surface temperatures of approximately 110 °C. Note that the exhaust outlet housed within the exhaust ejector was in clear view of the IR Equipment. This temperature was not recorded as an external surface temperature.

The lawn tractor equipped with engine 233, which was an OEM muffler and induction system configuration, had exposed surface temperatures of approximately 220 °C to 280 °C. The lawn tractor equipped with engine 232, which had the EFI system and catalyst-muffler, had exposed surface temperatures of approximately 200 °C.

In the case of both engine families, exposed surfaces were cooler for the catalyst-muffler equipped engines. This differed somewhat from the laboratory results, in part due to the more effective cooling of the catalyst-mufflers as installed in the chassis due to the re-routing of cooling air through the chassis and the addition of the exhaust ejectors.

Class II Lawn Tractors – 8.0 g/kW-hr systems

The lawn tractor equipped with engine 251, which used an OEM muffler, had exposed surface temperatures of approximately 200 °C as viewed from both sides of the tractor when cutting moderate to heavy grass, with peaks as high as 300 to 365 °C. The lawn tractor equipped with engine 253, which had the catalyst-muffler, had exposed surface temperatures of approximately 115 to 130 °C, with peaks of 160 to 190 °C.

The lawn tractor equipped with engine 256, which used an OEM muffler, had exposed surface temperatures of approximately 180 °C to 230 °C with peak temperatures of 290 to 320 °C. The lawn tractor equipped with engine 254, which had the catalyst-muffler, also had exposed surface temperatures of approximately 180 to 230 °C and peak temperatures of 290 to 320 °C.

In the case of both engine families, exposed surfaces were ether comparable (engine 254) or cooler (engine 253) for the catalyst-muffler equipped engines. This differed somewhat from the laboratory results, in part due to the more effective cooling of the catalyst-mufflers as installed in the chassis due to the re-routing of cooling air through the chassis and the addition of the exhaust ejectors.

Results of Hot-Soak Tests Conducted in the Field

Results of the hot soak tests conducted after approximately 30 to 45 minutes of grass cutting are presented in Figures 6-39 and 6-40 for the lawn mowers and lawn tractors, respectively, for data taken in Tennessee in the fall of 2005 and in Figures 6-41 and 6-42, respectively, for data taken in Florida in early 2006.

Tennessee Tests

At the two minute nominal refueling point following engine shut-down, two of the lawn mowers equipped with catalyst mufflers (engines 246 and 248) had comparable surface peak surface temperatures to the lawn mower equipped with the OEM muffler (engine 259). Two of the catalyst-muffler equipped lawn mowers (engines 244 and 249) were significantly cooler than the lawn mower equipped with the OEM muffler. The temperature decrease with time was more pronounced with the OEM configuration (259). Temperatures for all tested configurations were comparable at approximately five to six minutes following engine shut-down. Trends in soak temperatures relative to muffler shrouding and catalyst precious metal composition were similar to those observed during grass cutting. Catalyst washcoating formulations with higher palladium or rhodium content in place of platinum higher content tended to start the soak period with lower temperatures. Catalyst-mufflers using air shrouds and exhaust ejectors also tended to start the soak period with lower temperatures.

Florida Tests

At the two minute nominal refueling point following engine shut-down, all of the catalyst-muffler equipped lawn mower and lawn tractor configurations had lower peak surface temperatures than the OEM muffler configurations.

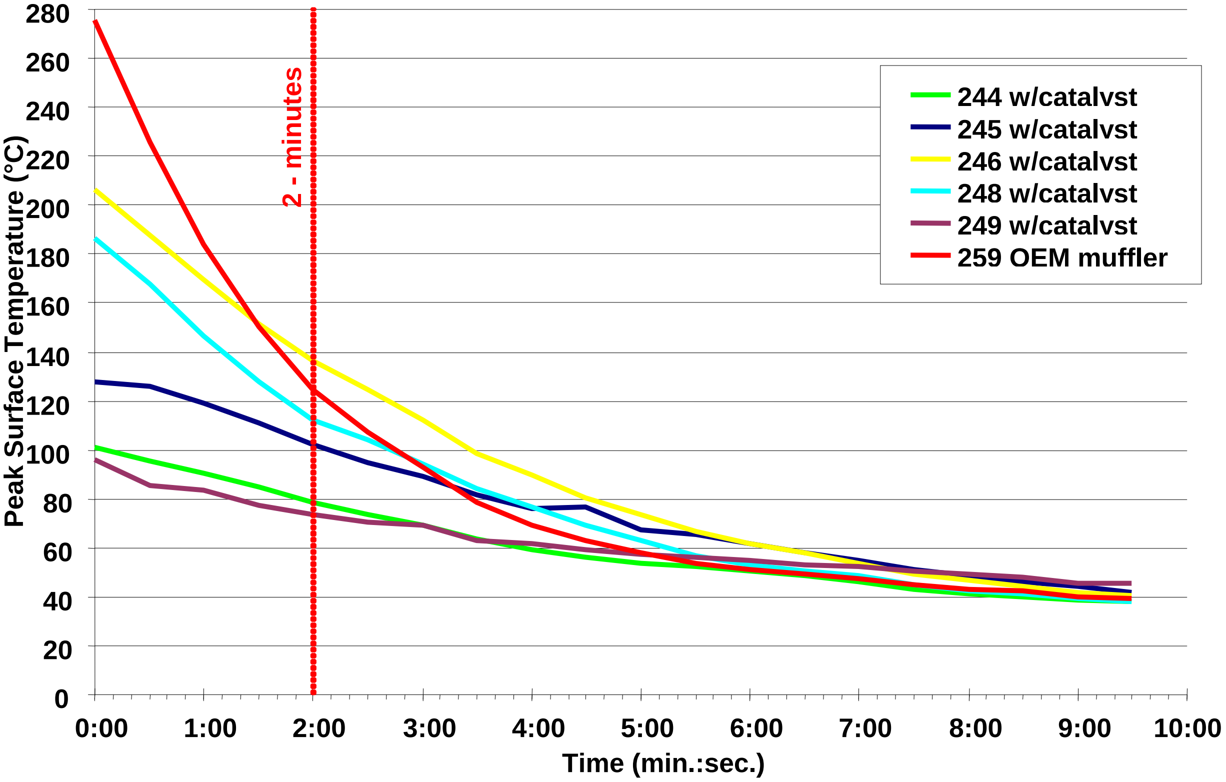


Figure 6-39: A comparison of peak surface temperatures for six lawn mowers measured using infrared thermal imaging during hot-soak tests immediately following engine shut-down after approximately 30 minutes of grass-cutting. At the nominal two minute refueling point, peak temperatures of the catalyst-muffler equipped lawn mowers were either comparable to (246, 248) or below (245, 244, 249) the lawn mower equipped with an OEM muffler (259). This data was acquired in SW Tennessee.

Both of the lawn tractors equipped with EFI and catalyst-mufflers (engines 231 and 232) were cooler than the OEM lawn tractors (engines 233 and 252) at the nominal two minute refueling point after engine shut-down. Surface temperatures for both EFI and catalyst-muffler configurations were at or below 100 °C for the entire soak period following engine shut-down. Surface temperatures for the lawn tractor equipped with engine 231 decreased slower than the lawn tractors equipped with engines 232, 233 and 252. Surface temperatures were comparable for the configurations with engines 232, 233 and 252 at approximately five to six minutes following engine shut-down.

Engine 231 had higher cylinder head and oil temperatures than engines 232 and 233 (but less than engine 252) and 231 also had somewhat less cooling capacity from the engine fan than engines 232 and 233. It is possible that the higher chassis and engine temperatures of lawn tractor equipped with engine 231 combined with the increased mass of the catalyst-muffler reduced the rate of heat transfer from the exhaust system following shut-down.

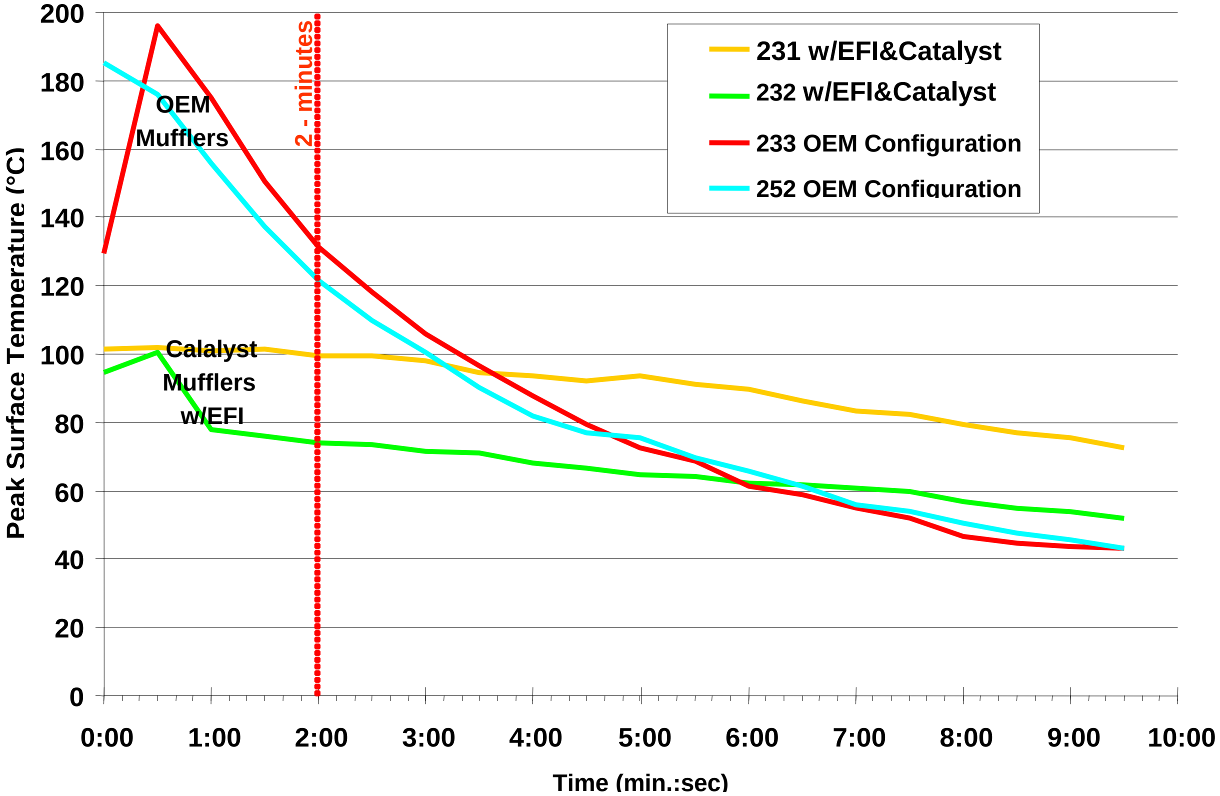


Figure 6-40: A comparison of peak surface temperatures for four lawn tractors measured using infrared thermal imaging during hot-soak tests immediately following engine shut-down after approximately 30-minutes of grass-cutting. At the nominal 2-minute refueling point, peak surface temperatures for the lawn tractors equipped with EFI and catalyst mufflers were comparable to (231) or significantly cooler than (232) the OEM configurations (233, 252). Note that engines 232 and 233 are both from one engine family, and that engines 231 and 251 are both from another engine family (refer to table 5-2). This data was acquired in SW Tennessee.

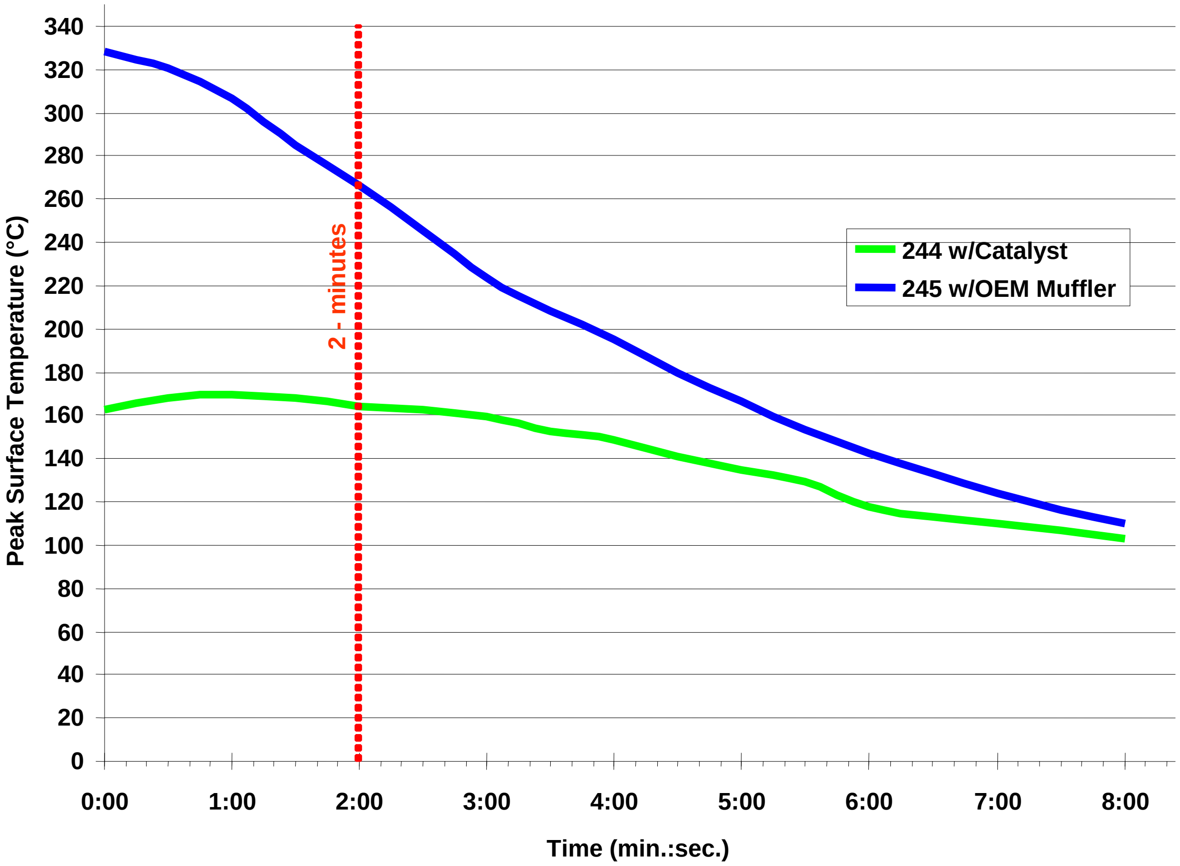


Figure 6-41: A comparison of peak surface temperatures for two lawn mowers measured using infrared thermal imaging during hot-soak tests immediately following engine shut-down after approximately 30 minutes of grass-cutting. This was a repeat of hot-soak testing for engines 244 and 245 at a higher ambient temperature (30 °C vs. 18.5 °C), and with engine 245 using an OEM muffler. At the nominal two minute refueling point, peak temperatures of the catalyst-muffler equipped lawn mower (engine 244) was below that the lawn mower equipped with an OEM muffler (engine 245). The range of surface temperatures encountered were approximately 60 °C higher than those measured at lower ambient temperature conditions (Figure 6-39). This data was acquired in Florida.

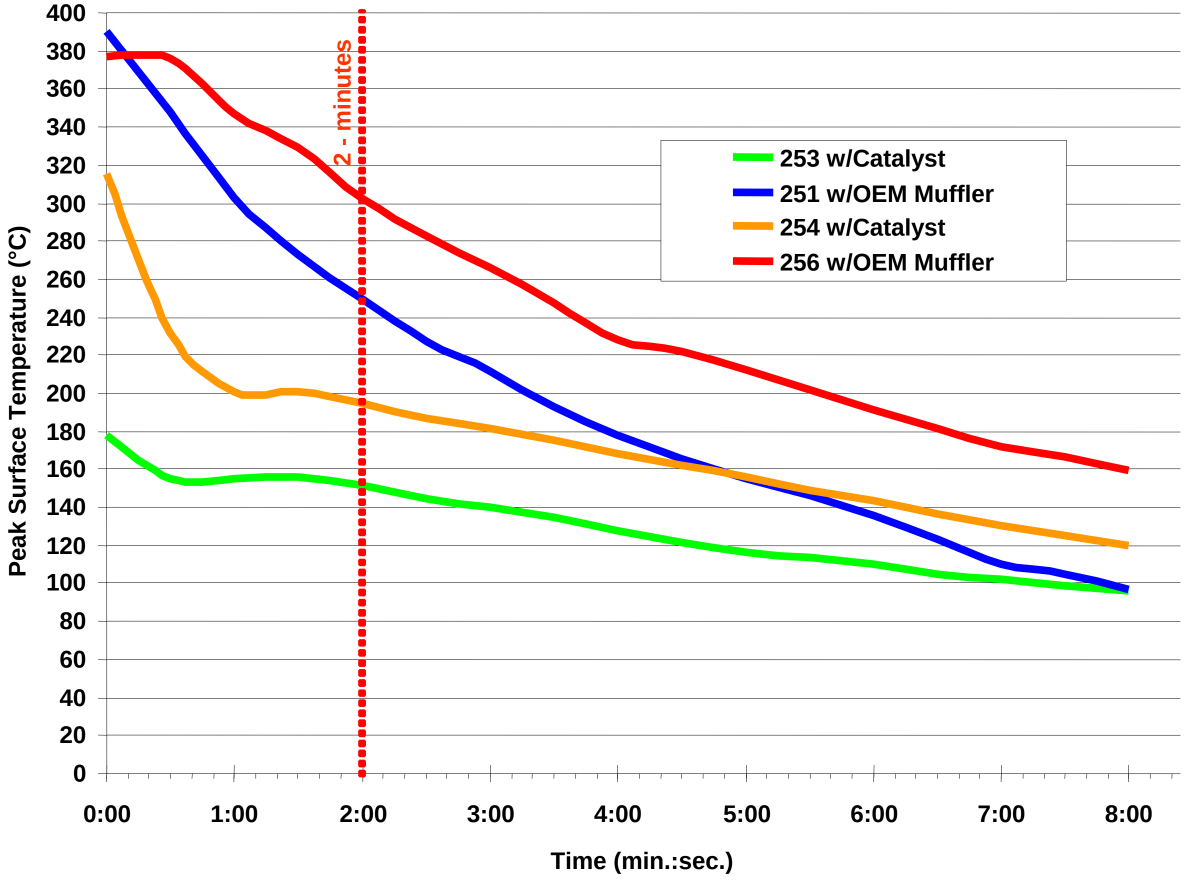


Figure 6-42: A comparison of peak surface temperatures for four lawn tractors measured using infrared thermal imaging during hot-soak tests immediately following engine shut-down after approximately 30-minutes of grass-cutting. At the nominal 2-minute refueling point, peak surface temperatures for the lawn tractors equipped with catalyst mufflers (engines 251 and 256) were significantly cooler than the OEM muffler configurations (engines 251 and 256). Note that engines 251 and 253 are both from one engine family, and that engines 254 and 256 are both from another engine family (refer to table 5-2). This data was acquired in Florida.

Idle Testing

The turf surface temperatures for the catalyst-muffler equipped lawn tractors were either comparable (engine 254) or reduced (engine 253) relative to the turf surface temperatures measured during idling of the lawn tractors with the OEM mufflers (engines 251 and 256). The variation in turf temperatures was due entirely to wind gusts. Wind breaks were improvised on two sides of the lawn tractors, but light wind gusts were observed to cause an approximately 10 °C to 20 °C oscillation in peak turf temperatures measured for engines 254 and 256. Wind was relatively calm during the measurements with engines 251 and 253, which reduced the variability in peak turf temperatures to approximately 5 °C to 10 °C. Note that engines 251 and 253 are both from one engine family, and that engines 254 and 256 are both from another engine family (refer to table 5-2). This data was acquired in Florida.

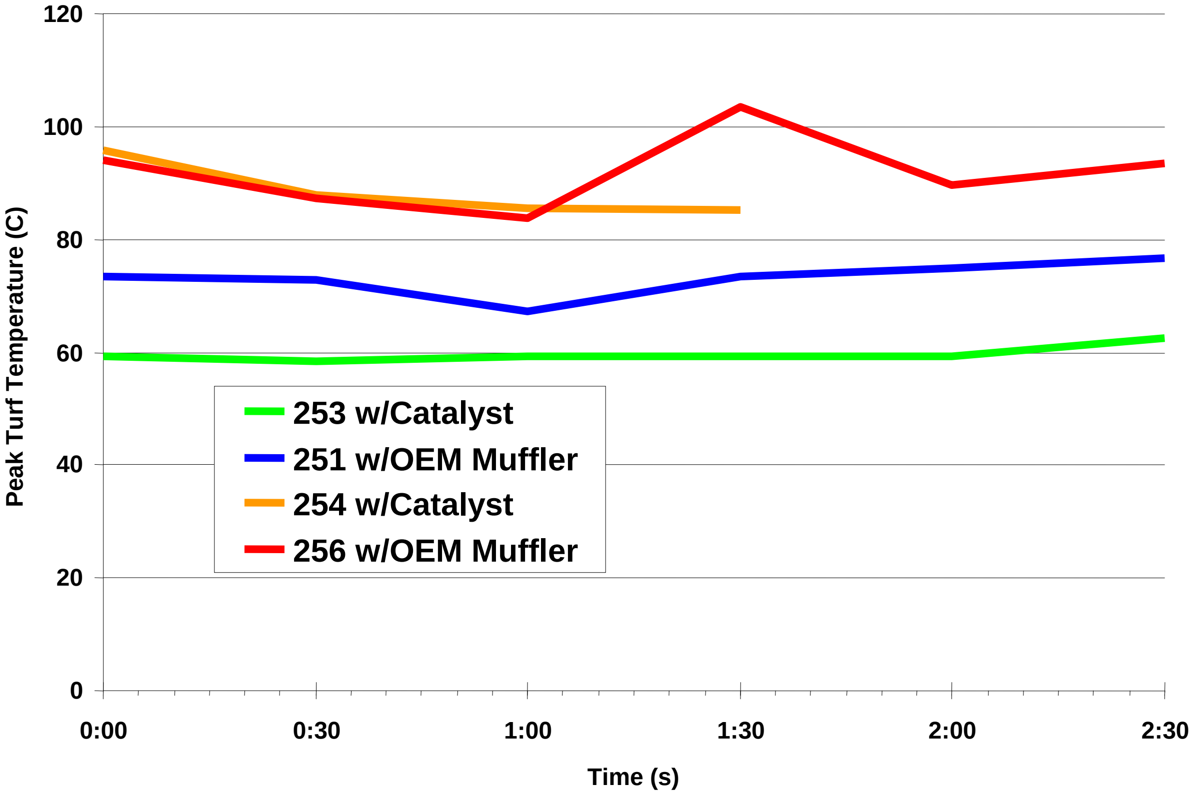


Figure 6-43: A comparison of peak turf surfaces measured underneath and immediately in front of four lawn tractors parked and operating at high-idle. Measurements were taken following a 5-minute turf temperature stabilization period. The turf surface temperatures for the catalyst-muffler equipped lawn tractors were either comparable (engine 254) or reduced (engine 253) relative to the turf surface temperatures measured during idling of the lawn tractors with the OEM mufflers (engines 251 and 256).

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[1] “Control of Emissions From Nonroad Spark-Ignition Engines, Vessels, and Equipment Document”, Docket ID EPA-HQ-OAR-2004-0008-0328, “Safety Study Supplemental Data”.

7. Design and Process Failure Mode and Effects Analyses (FMEA) to Assess NHH Incremental Safety Risk

A. BACKGROUND

In addition to the laboratory and field work described in previous chapters, EPA contracted with Southwest Research Institute of San Antonio, Texas to conduct design and process Failure Mode and Effects Analyses. The full text of the SwRI report is contained in an Appendix to this study.

An FMEA is an engineering analysis tool to help engineers and other professional staff on the FMEA team to identify and manage risk. In an FMEA, potential failure modes, causes of failure, and failure effects are identified. The primary purpose of the FMEA is to identify those causes of failure modes with the greatest potential for adverse effect both in terms of frequency of occurrence of the cause of the failure and in the severity of the consequences of the failure. Within an FMEA the multiplicative product of the numerical values assigned to the frequency of occurrence of the causal mechanism and severity of the effect of the failure is referred to as risk probability. This risk probability is used by the FMEA team to rank problems for potential action to reduce or eliminate the causal factors. The focus of the FMEA is on identifying and prioritizing the causal factors for the failure modes, because the causal factors are the elements that a manufacturer can consider in order to reduce the adverse effects that might result from a failure mode. While data is employed to the greatest degree possible, ultimately the process depends on the professional judgment by members of the FMEA team.

Risk and risk probability are not the same. In traditional safety analysis, risk usually refers to the likelihood of the occurrence of a hazardous outcome. The occurrence of a hazardous outcome in a given event is much less than the occurrence of the event itself (e.g., most trip and fall events do not lead to broken bones). In this context, the risk probability is not the risk that an actual hazardous outcome will occur in a given event, but is a tool to rank the relative risk of events based on the frequency of the causal factor leading to a failure mode and the severity of the potential effect of the failure. The frequency used to determine risk probability is the estimate of the frequency of the potential cause of the failure mode not the frequency of the potential effect(s) if the failure mode were to occur. For example, one failure mode that was evaluated is backfiring from the engine. One factor that could cause backfire would be a richer fuel mixture. A richer mixture does not always lead to backfire, if it did then there is always an increased risk of fire or burn. The FMEA analysis looks at the probability that the causal factor, (the richer fuel mixture), would occur, and the severity of the outcome if the richer fuel mixture did lead to backfire and a fire or burn. The analysis does not try to determine the likelihood that richer fuel mixture will in fact lead to fire or burn, instead, the analyses basically assumes the worst case - the backfire does occur and leads to a fire or burn. The analysis looks at various failure modes from this worst case perspective, in order to rank the highest priority issues to address. Thus, for FMEA purposes the risk probability associated with richer fuel mixture may be the same for all potential outcomes of a richer fuel mixture because the probability of the causal factor of richer fuel mixture occurring is the same. However, the hazardous outcome of a fire or burn occurring is clearly not the same as the probability that a richer fuel mixture will occur. Determining hazard risk is beyond the scope of a design or process FMEA.

B. THE WORK CONDUCTED BY SwRI

In doing this work for EPA, SwRI used the basic FMEA approach contained in SAE Standard J1739.[1] This approach requires the FMEA team to identify and characterize the systems and subsystems involved and then for each subsystem list:

1. The item/function being analyzed
2. The potential cause(s)/mechanism(s) of the failure (both primary and contributing, as appropriate)
3. The potential failure mode
4. The potential effect(s) of the failure
5. The classification of the effect
6. The severity of the failure mode
7. The frequency of occurrence of the potential cause(s)/mechanism(s)
8. Risk Probability Number (RPN) [(6)x(7)]

SAE J1739 provides detailed and helpful guidance to the team on how to set-up and conduct the FMEA. However, the FMEA is a tool and is often tailored by an FMEA team to help better meet project needs. In this case, looking at the incremental risk question raised by EPA required SwRI to make adaptations in the way they applied the SAE protocol. These are described in the full text of the SwRI report attached to this study.

This FMEA covered equipment using Class I and Class II engines. For Class I engines, the equipment identified was a typical walk-behind lawnmower (WBM). For Class II, the equipment identified was a ride-on lawnmower (ROM). Two different types of FMEAs were prepared. The first was design FMEAs for both the WBM and ROM. The second were three process FMEAs covering refueling, maintenance, and shutdown and storage of the equipment.

These FMEAs were conducted to identify and assess potential differences in risk probability between engines and equipment meeting EPA Phase 2 emission standards and properly designed engines and equipment meeting potential EPA Phase 3 emission standards. For Phase 2 Class I and II powered-equipment, SwRI used typical currently produced equipment/engines. Obviously, production Phase 3 equipment is not available. The characteristics of properly designed Phase 3 equipment/engine as considered by SwRI are presented in Table 7-1.

Table 7-1. Projected Phase 3 Engine Characteristics

Item No.	Class I Lawnmower Engine	Class II Ride-on Mower Engine
1	Application of catalyst (moderate activity 30-50%) designed to minimize CO oxidation, maximize NO_x reduction, with low HC oxidation efficiency at high exhaust-flow-rates and high HC oxidation efficiency at low-exhaust flowrates. This design is expected to minimize catalyst exotherm.	Application of catalyst (moderate activity 30-50%) designed to minimize CO oxidation, maximize NO_X reduction, with low HC oxidation efficiency at high exhaust flowrates and high HC oxidation efficiency at low-exhaust flowrates. This design is expected to minimize catalyst exotherm.
2	Cooling and shrouding of engine and muffler to minimize surface temperatures. Use of heat shielding and/or air-gap insulated exhaust components to minimize surface temperatures.	Cooling and shrouding of engine and muffler to minimize surface temperatures. Use of heat shielding and/or air-gap insulated exhaust components to minimize surface temperatures.
3	Design flow paths/baffles through the mufflers to incorporate flame arresting design features, to improve heat rejection to muffler surfaces and to spread heat rejection over a large surface area of the muffler. This will reduce the incidence of backfire and reduce localized hot spots.	Design flow paths/baffles through the mufflers to incorporate flame arresting design features, to improve heat rejection to muffler surfaces and to spread heat rejection over a large surface area of the muffler. This will reduce the incidence of backfire and reduce localized hot spots.
4	Different catalyst substrates (ceramic, metal monolith, hot tube, metal mesh) can be successfully used.	Different catalyst substrates (ceramic, metal monolith, hot tube, mesh) can be successfully used.
5	The use of air ejectors to cool exhaust gases at the muffler outlet and to improve cooling of heat shielding.	The use of air ejectors to cool exhaust gases at the muffler outlet and to improve cooling of heat shielding.
6	Use of a small amount of passive supplemental air to improve exhaust chemistry at light load, but designed so bulk exhaust remains rich of stoichiometry at all conditions, and flow-limited at high exhaust flowrates. This design minimizes risk of excessive catalyst exotherm.	Use of carburetor recalibration to improve exhaust chemistry at light load conditions.
7	Use of fuel filter and/or improved design needle and seat in carburetor to minimize problems caused by fuel debris.	Improved air/fuel ratio control through tighter manufacturing tolerances to minimize variation.
8	Improved intake manifold design to reduce intake manifold leaks.	No anticipated design changes.
9	Cooling system designed to reduce the accumulation of debris, including the use of a mesh or screen on cooling fan inlet, when lacking in current design.	Cooling system designed to reduce the accumulation of debris.
10	Improved ignition system design to be more reliable and durable than on Phase 2.	Improved ignition system design to be more reliable and durable than on Phase 2.

Table 7-1. Projected Phase 3 Engine Characteristics (continued)

11	Improved component design and manufacturing processes to reduce air-fuel ratio production variability to stabilize engine performance and emissions.	Component changes are not expected. Improved manufacturing processes to reduce air-fuel ratio production variability to stabilize engine performance and emissions.
12	Locate fuel tanks away from heat sources.	Locate fuel tanks away from heat sources.
13	Use of carburetors with appropriate idle circuits, float-bowl vent, and automatic choke or improved primer bulb. This will improve fuel system reliability.	Use of carburetors with appropriate idle circuits, float-bowl vent, and automatic choke. This will improve fuel system reliability.
14	Locate the exhaust port away from the carburetor/fuel line to minimize carburetor heating.	No anticipated design changes.
15	Improved exhaust system design and materials for better durability and reliability.	No anticipated design changes.
16	Improved muffler/catalyst/equipment design since currently, the muffler designs do not incorporate catalysts.	Improved muffler/catalyst/equipment design since currently, the muffler designs do not incorporate catalysts.
17	Evaporative emission controls: hoses, tank, cap, and evaporative emission control system.	Evaporative emission controls: hoses, tank, cap, and evaporative emission control system.
18	As Needed: non-contact, bi-metal thermal switch to disable ignition system to shut engine down in event of excessive temperature.	As Needed: non-contact, bi-metal thermal switch to disable ignition system to shut engine down in event of excessive temperature. Manufacturers will need to consider the potential trade-off of disengaging engine power on ride-on equipment if were to occur on a slope.

C. DESIGN FMEA

The design FMEAs looked at the subsystems/components likely to be modified for compliance with potential Phase 3 exhaust and evaporative emission control requirements and those affected by the modification. Twelve systems/subsystems were evaluated for both the WBM (Class I) and the ROM (Class II). This broad approach was deemed essential because of the technical interdependency among these systems in creating power and the potential interactions among these systems in failure mode situations. The twelve subsystems evaluated included:

1. intake air filter
2. carburetor system
3. governor
4. intake manifold, port, valve, and seals
5. block, power head
6. exhaust valve and seal
7. exhaust manifold, muffler, muffler shroud, and gasket
8. supplemental air (venturi)
9. catalyst
10. cooling system

11. ignition system
12. fuel tank and line

The design FMEAs were structured and conducted in the following manner: (The reader may find it useful to refer to the template in Figure 7-1.)

Figure 7-1: Sample FMEA Template.

Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph 2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs. Ph 3)	Notes

First the system and function were identified. Next, for each item identified, each cell of the columns of the FMEA was completed. This relied heavily on SwRI's understanding of small engines, combustion, fuels, and how the primary and contributing causes can translate into potential failure modes. The failure modes of the subsystem were often identified as a potential cause (primary or contributing) of a potential failure mode of other engine system.

Once the potential failure modes were identified, the team ranked the estimated occurrence rate. Then the team identified the potential effects (usually more than one) and ranked their individual severity. Information from the CPSC databases discussed in Chapter 4 was instrumental in linking potential failure modes and effects. The rankings for the severity of the failure mode and the frequency of occurrence of potential cause were drawn from the tables (shown below) which were taken from the SwRI report. For the severity classification any failure mode involving a potential burn or fire was ranked as a 9 or 10, respectively, while an increase in the risk of fire or burn was ranked as a 9. The final steps in the FMEA process were to assign the effect to one of four classes (safety, regulatory compliance, performance, other) and to calculate the risk probability number for each row by multiplying the occurrence and severity values. The entire process was completed for each of the twelve subsystems for the WBM Phase 2, WBM Phase 3, ROM Phase 2, and ROM Phase 3 equipment. Calculating the delta RPN shown in the template required a subtraction of the RPN value for the Phase 2 and Phase 3 analysis for each item. The full results for these four design FMEAs are in the attached SwRI reports.

Table 7-2: Severity Ranking Scale

Ranking	Effect	Severity of Effect – Customer
10	Hazardous	Hazardous effect. Safety Related. Regulatory non-compliant
9	Serious	Potential hazardous effect. Able to stop without mishap. Regulatory compliance in jeopardy.
8	Extreme	Item inoperable, but safe. Customer very dissatisfied
7	Major	Performance severely affected, but functional and safe. Customer dissatisfied
6	Significant	Performance degraded, but operable and safe. Customer experiences discomfort
5	Moderate	Performance moderately affected. Fault on non-vital requires repair. Customer experiences some dissatisfaction
4	Minor	Minor effect on performance. Fault does not require repair. Non-vital fault always noticed. Customer experiences minor nuisance.
3	Slight	Slight effect on performance. Non-vital fault noticed most of the time. Customer slightly annoyed.
2	Very Slight	Very slight effect on performance. Non-vital fault may be noticed. Customer is not annoyed.
1	None	No effect.

Table 7-3: Occurrence Ranking Scale.

Ranking	Probability	Likely Failure Rates
10	Almost Certain	Greater than / Equal to 1 in 2
9	Very High	1 in 3
8	High	1 in 8
7	Moderately High	1 in 20
6	Medium	1 in 80
5	Low	1 in 400
4	Slight	1 in 2000
3	Very Slight	1 in 10,000
2	Remote	1 in 50,000
1	Almost Impossible	≤1 in 500,000

Note 1: For the Design FMEA the Occurrence Ranking is related to the design life of the equipment.
Note 2: For the Process FMEA the Occurrence Ranking is related to a one-year operation period.

D. PROCESS FMEA

As discussed in Chapter 4, input received from various sources and the CPSC databases revealed three processes which to some degree lead to problems in-use. The process FMEAs conducted by SwRI addressed refueling, equipment shut down and storage, and maintenance (equipment cleaning, oil/filter change, spark plug change, blade sharpening, and drive belt replacement). While some of the information and results from the design FMEA would carry across to the process FMEAs (e.g., air filter problems), a key difference between the analyses of these activities in the design and process FMEAs is the introduction of the operator as a factor. Otherwise, the process FMEAs were conducted very much like the design FMEAs, with heavy reliance on the SwRI technical expertise and inputs gleaned from the CPSC databases.

E. FMEA RESULTS

The purpose of the FMEAs was to identify and assess change in engines, equipment, and operation that could potentially impact safety when moving from Phase 2 compliant product to Phase 3 compliant product. To meet this objective there were two further steps necessary to put the FMEA results in a format useful for this study. The first is related to the “Classification of Effect” column. Above we indicated that the study divided all of the potential effects into one of four categories; of those four, only safety is relevant here. Second, as was presented above, the analysis should be presented in a format that shows incremental RPN differences between Phase 2 and Phase 3 product. The differences between the outcomes of the Phase 2 and Phase 3 design and process FMEAs are instructive in characterizing potential safety concerns in each category and identifying potential incremental safety risks. This is possible because the delta RPN number is indicative of the incremental change in risk from the engineering perspective. From the viewpoint of a designer, a positive delta RPN would indicate a directional reduction in the incremental risk, a zero value would represents essentially no incremental change, and a negative delta RPN would suggest a directional increase in risk. Tables 7-4 to 7-8, shown below, present the design and process FMEA results for the safety-related items from the attached SwRI report.

F. DISCUSSION OF DESIGN FMEAs FOR CLASSES I AND II

A review of the analyses presented in Tables 7-4 and 7-5 clearly indicates that for both the WBM (Class I) and ROM (Class II) FMEAs, the overall FMEAs are comparable for Phase 2 and the Phase 3 compliant equipment. Table 7-4 presents the safety-related items of the FMEA for WBMs. In the WBM (Class I engine) FMEA, SwRI identified 24 failure modes with the potential for an impact on safety. In comparing the Phase 3 and Phase 2 RPNs, 11 indicated a positive RPN delta and thus the potential for a directional improvement in safety, while one indicated a negative RPN delta and thus the potential for a directional degradation in safety, and 12 indicated no overall change in RPN. Similarly, Table 7-5 presents the safety-related items of the FMEA for ROMs. In the ROM (Class II engine) FMEA, SwRI identified 25 failure modes with the potential for an incremental safety effect. In comparing the Phase 3 and Phase 2 RPNs, 8 indicated a positive RPN delta and thus the potential for a directional improvement in safety, while one indicated a negative RPN delta and thus the potential for a directional degradation in safety, and 16 indicated no overall change in RPN.

Chapter 4 identified seven scenarios for evaluation, and indeed the FMEAs also identified many of the potential causes listed in Chapter 4 as potential failure modes. The FMEA outcomes for these items will be discussed further in Chapter 8.

There was one hazard pattern identified in the CPSC IPII database where the cause was unknown. In Chapter 3 this is identified as “Unspecified: For reasons unspecified, the running lawn mower catches fire/explodes.” With no detail, it is not wise to speculate on the specific cause(s) of these events. While these types of incidents are not directly addressed in the FMEA a review of the FMEA tables and the details on incidents of this nature may provide some perspective. Major engine malfunction is addressed in the Class I and Class II FMEAs with the conclusion that there is no change in risk probability number. Also, fuel line and fuel tank leak or failure is assessed in the Class I and Class II design FMEAs with the general conclusion that the possibility that some manufacturers may move fuel tanks to address fuel evaporative emission controls could at least directionally reduce the risk probability number for Phase 3 versus Phase 2 equipment. In addition, the Class I and Class II FMEAs indicate a lower risk probability number for debris fires for a properly designed Phase 3 system compared to a current Phase 2 system. Thus, based on this assessment, to the degree that these types of potential causes lead to fire in operation, EPA believes that in an overall sense there will not be an increase in this type of fire for a properly designed Phase 3 system.

The design FMEAs looked at the subsystems/components likely to be modified for compliance with potential Phase 3 exhaust and evaporative emission control requirements and those affected by the modification. Twelve systems/subsystems were evaluated for both the WBM (Class I) and the ROM (Class II). This broad approach was deemed essential because of the technical interdependency among these systems in creating power and the potential interactions among these systems in failure mode situations. The potential effect of failure modes on the catalyzed muffler performance was considered in each item evaluated. No system or subsystem was considered in isolation.

Considering this systems view and the interactions among the subsystems it is worthwhile to discuss the issue of enleanment, an increase in the intake A/F ratio above the design value. This can occur because of an increase in the available air or a decrease in the available fuel, and is usually a result of a failure of a component or subsystem upstream of the exhaust manifold. Concerns have been expressed that enleanment on an engine with a catalyzed muffler could lead to fire and burn risk because the activity of the catalyst would enhance CO oxidation in the presence of the extra air. However, increased oxidation also occurs in a non-catalyst muffler because the muffler acts like a thermal reactor.

Even without potential failures exhaust system surface temperatures are above the levels needed for contact burns to occur. With enleanment the surface temperatures would still be above the temperatures needed for thermal burns to occur. The FMEA identified three potential failure modes related to leaner mixtures, including situations where the air filter, the carburetor, or the intake air manifold failed to function as designed. For all three potential failure modes even with the potential for hotter exhaust gas, hotter exhaust system surface temperatures, and/or hotter engine surface temperatures, the RPN related to fire and burn risk is zero or improved for Phase 3 compared to Phase 2.

The Phase 3 catalyzed system incorporates improvements which will reduce the surface temperature exposed to the user. The improvements include cooling air from the fan directed over the muffler and the heat shield designed to cover the entire muffler and direct that cooling air around the muffler and out designated areas for maximum muffler cooling. Therefore, increased temperatures resulting from differing exhaust conditions would not result in a significant increased temperature to the user over that of a Phase 2 system experiencing the same exhaust conditions.

Process FMEAs

SwRI also performed process FMEAs on the WBM and the ROM to assess potential failure modes and effects for three of the most common events in the life cycle of the engine and equipment. These included refueling, shutdown and storage, and maintenance. A review of the information provided by CPSC indicates current in-use safety problems in all three areas.

First, with regard to refueling, in Table 7-6, SwRI identified 25 aspects of the operation with potential impacts on safety. Of these, 12 involved the actual dispensing of fuel from a gas can into the equipment tank. SwRI's analysis indicated no change in RPN for Phase 2 and Phase 3 equipment for any of the 25 events involving refueling.

The second process FMEA (Table 7-7) involved shutdown and storage of equipment after use. The IPII data base provided by CPSC included a number of situations where, for various reasons, equipment stored either outdoors or indoors after use led to a grass or structure fire. In most cases the causes were not clear, but were presumably related to grass/leaf debris or combustible material coming into contact with hot surfaces or the ignition of fuel vapor by sources not related to the mower unit. SwRI identified 15 items with potential safety implications related to shutdown and storage. In none of these did the FMEA indicate any differences in RPN between Phase 2 and Phase 3 equipment.

The third process FMEA (Table 7-8) involved different aspects of common maintenance practices including cleaning equipment, changing the oil/filter, changing the spark plug, sharpening the cutting blade, and replacing the drive belt. Of the 16 different items identified, SwRI identified five in which the RPN improved slightly. In each of these, the potential for fuel spillage on the operator or on hot surfaces during maintenance would be reduced because of tank and cap changes brought on by potential EPA fuel evaporative emission control requirements.

G. CONCLUSION

The RPN values are the output from the FMEA which the engineer would use to rank and prioritize actions which might be taken to reduce potential risk. Since EPA is most interested in assessing the incremental risk of going from Phase 2 to Phase 3, the delta RPN as presented in the SwRI analyses is instructive in understanding how design and performance changes on the engines/equipment might affect in-use fire and burn risk.

When comparing the delta RPN results for the Phase 2 WBM and Phase 3 WBM design FMEAs and comparing the delta RPN results for the Phase 2 ROM and Phase 3 ROM design FMEAs the engineer would conclude that the Phase 3 equipment does not present an increase in risk of fire and burn relative to Phase 2. The FMEAs for both WBMs and ROMs give comparable and in some cases directionally positive results. The engineer's decisions on ranking and prioritizing risks to address would not be significantly different for a properly designed Phase 3 system compared to a current Phase 2 system.

An inspection of the RPN delta columns in Tables 7-4 to 7-8 shows only modest changes. The vast majority of RPN deltas were positive or zero for the safety classification indicating either a directional improvement or no change in risk. This indicates that from the FMEA perspective, the potential causes identified in the seven scenarios in Chapter 4 would not be worse for a properly designed Phase 3 system and some would be better.

This analysis includes a catalyzed muffler in the Phase 3 systems. Since a Phase 2 system does not have a catalyzed muffler, the potential exists to identify failure modes related to the inclusion of the catalyst in the muffler. In the Phase 3 WBM and ROM FMEAs, the catalyzed muffler was considered in every item evaluated. In the beginning of this chapter EPA discussed that the rationale for selecting twelve subsystems in the WBM and ROM FMEAs, was to ensure that the analyses captured the technical interdependency among these subsystems in creating power and the potential interactions among these systems in failure mode situations. That is to say, problems in air intake, ignition, carburetion, fuel storage etc all had the potential to manifest themselves as causal effects for fire or burn problems related to the catalyzed muffler. However, of the approximately twenty five items evaluated in both the WBM and ROM design FMEAs where the catalyst was considered in each item, the analyses identified only one type failure mode which led to a negative delta RPN. The vast majority had a positive or zero delta RPN leading to the conclusion catalyst-equipped WBMs and catalyst-equipped ROMs can be implemented without an increase in risk of fire or burn.

The one item with a negative delta RPN in both the Class I and Class II design FMEAs was related to either an incorrect or improperly installed catalyst in the muffler where there was not one in the Phase 2 system. In this case, the FMEA performed its intended function - to identify for the designer potential failure modes and effects to allow for an appropriate response as necessary. In this case the severity was rated a 10 based on burn or fire concerns and the frequency of the failure was rated as a 2 (remote) by SwRI. The chance of this occurring truly seems remote since catalyst geometries will by definition partially eliminate mistakes (the wrong catalyst won't fit in the space allocated) and there are very tight finite limits on catalyst wash coating which would limit the severity. Conceptually, this potential problem is similar to one not identified in the Phase 2 FMEAs, that being the mis-installation of the muffler or an incorrect muffler. In this case there would be potential problems related to backpressure or changes in cooling air flow which could affect fire and burn risk. No such problems were identified in the CPSC databases. Nonetheless, if the FMEA team decided to address this concern for Phase 3 engines there are a number of approaches including QA/QC processes to address potential catalyst vendor or installation problems or improved heat shielding. Thus, EPA does not see this potential failure mode as creating an in-use risk.

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[1] SAE J1739, "Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)", SAE International, August 2002.

Table 7-4: Class I Safety FMEA Items

Class I Safety FMEA Items

Ref. Item No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph 2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Notes
1	Intake Air Filter	Degradation or tear of filter element, wrong filter or dirty or missing filter. Prefilter not oiled	richer mixture	backfire	fire or burn	1_Safety	10	3	30	20	10	2	10	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. That fact drives a reduction in the Occurrence ranking.
2	Intake Air Filter	Degradation or tear of filter element, wrong filter or dirty or missing filter. Prefilter not oiled	leaner mixture	hotter exhaust	fire or burn	1_Safety	10	3	30	30	10	3	0	The rankings are the same with or without a catalyst because there will be no increase in burn risk with the application of a properly designed catalyst. The effect could be mitigated by the presence of a thermal switch.
3	Carburetor System	Restriction in fuel passages, wrong jets in production or production variability	leaner mixture	Higher temperature in engine and catalyst	fire or burn	1_Safety	10	4	40	40	10	4	0	The rankings are the same with or without a catalyst. Any effect that the catalyst might have on temperature level is offset by the expected improvements in air cooling of the manifold system on Phase 3 products. If the change in temperature is significant the effect could be mitigated by the presence of a thermal switch.
4	Carburetor System	Float breaks, debris in float needle, or wrong jets in production, choke stuck closed or production variability	richer mixture	backfire	fire or burn	1_Safety	10	5	50	40	10	4	10	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. That fact drives a reduction in the Occurrence ranking.
5	Carburetor System	gasket failure, or needle valve stuck open, or cracked primer bulb	leakage of fuel to mower deck, air filter or elsewhere (i.e. out of air filter)	fuel ignites	fire or burn	1_Safety	10	2	20	20	10	2	0	The rankings are the same with or without a catalyst because exposed muffler temperatures are nominally equivalent. Fuel can be ignited by hot surfaces or the ignition system.

Class I Safety FMEA Items

Ref. Item No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph 2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Notes
6	Carburetor System	gasket failure, or needle valve stuck open, or cracked primer bulb	leakage of fuel to mower deck, air filter or elsewhere (i.e. out of air filter)	fuel puddles	fire or burn	1_Safety	10	4	40	40	10	4	0	The rankings are the same with or without a catalyst because exposed muffler surfaces have been shown to be nominally equivalent in Phase 2 (no catalyst) and Phase 3 (catalyzed) prototype systems.
7	Governor		Malfunction-ing governor	open governor causes engine overspeed	catastrophic failure (potential injury due to flying parts)	1_Safety	9	2	18	18	9	2	0	Engine failure caused by overspeed. The rankings are the same with or without a catalyst.
8	Intake Manifold	None Crack or leak in manifold	leaner mixture	Engine, exhaust system and catalyst run hotter	fire or burn	1_Safety	10	9	90	40	10	4	50	The lower occurrence for Phase 3 is due to the expected improvement of the manifold system for Phase 3 products. The effect could be mitigated by the presence of a thermal switch.
9	Block	Higher thermal load	higher engine temperatures	Engine failure (internal component seizure, broken valve or spring, excess wear)	catastrophic failure (potential injury due to flying parts)	1_Safety	9	4	36	36	9	4	0	Engine failure caused by excessive temperatures. The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
10	Block	Higher thermal load	higher engine temperatures	Engine failure (internal component seizure, broken valve or spring, excess wear)	fire or burn	1_Safety	10	4	40	40	10	4	0	Engine failure can result in contact with hot metal or fluids. The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
11	Exhaust Manifold	None	loosening of muffler, manifold or failed gasket (gasket is less common on Class I vertical shaft engines)	exhaust leak	fire or burn	1_Safety	10	6	60	40	10	4	20	The lower Phase 3 occurrence is due to the Phase 3 improved exhaust system design.

Class I Safety FMEA Items

Ref. Item No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph 2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Notes
12	Exhaust Manifold	Debris accumulation	reduction in engine cooling and increased muffler temperatures	ignition of debris adjacent to muffler	fire	1_Safety	10	3	30	20	10	2	10	The lower occurrence for the Phase 3 is due to the improvement of the air ducting for cooling and control of debris accumulation. In addition, fan inlet screens are expected on all Phase 3 engines. The failure mode could be mitigated by the presence of a thermal switch.
13	Exhaust Manifold		removal or mechanical failure of the shroud	loss of muffler shroud	fire or burn	1_Safety	10	3	30	20	10	2	10	The lower occurrence for the Phase 3 is due to the improvement of the air ducting for cooling and shroud design.
14	Catalyst	None Manufacturing, supplier or installation problem	incorrect or improperly installed catalyst	excessive catalyst performance	fire or burn	1_Safety	1	1	1	20	10	2	-19	The Phase 2 ranking is low by definition, since Phase 2 does not have a catalyst. For Phase 3, the severity ranks high due to the potential safety impact. The effect could be mitigated by the presence of a thermal switch.
15	Cooling System		cooling system shroud failed	loss of cooling to engine block and muffler system	burn risk	1_Safety	9	2	18	18	9	2	0	The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
16	Cooling System	None	plugging of cooling passages due to debris	reduction of engine cooling	burn risk	1_Safety	9	5	45	36	9	4	9	By definition of the Phase 3 product, the improved design features for Phase 3 results in a slight reduction in Occurrence. The effect could be mitigated by the presence of a thermal switch.
17	Ignition System	None None	plug bad, short in plug wire, failed coil, loose flywheel, magneto, ignition module failure	weak or intermittent spark (misfire)	excessive muffler or catalyst temperatures and increased burn risk	1_Safety	9	5	45	27	9	3	18	The lower occurrence for the Phase 3 is due to the improved ignition system for Phase 3 products. The effect could be mitigated by the presence of a thermal switch.
18	Ignition System	plug bad, short in plug wire, failed coil, loose flywheel, magneto	loss of spark	backfire (misfire)	fire or burn	1_Safety	10	6	60	40	10	4	20	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. That fact drives a reduction in the Occurrence ranking.

Class I Safety FMEA Items

Ref. Item No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph 2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Notes
19	Fuel Tank		leak of tank or line	fuel puddles	fire or burn	1_Safety	10	5	50	40	10	4	10	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
20	Fuel Tank	None	leak of tank or line	fuel puddles	operator fuel exposure	1_Safety	9	5	45	36	9	4	9	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
21	Fuel Tank	None	leak of tank or line	fuel leaks on hot component	fire or burn	1_Safety	10	4	40	30	10	3	10	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
22	Fuel Tank	None High muffler or catalyst temperatures near fuel lines	fuel tank or line melted	fuel puddles	fire or burn	1_Safety	10	3	30	20	10	2	10	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
23	Fuel Tank	High muffler or catalyst temperatures near fuel lines	fuel tank or line melted	fuel puddles	operator fuel exposure	1_Safety	9	3	27	18	9	2	9	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
24	Fuel Tank	High muffler or catalyst temperatures near fuel lines	fuel tank or line melted	fuel leaks on hot component	fire or burn	1_Safety	10	2	20	20	10	2	0	The rankings are the same with or without a catalyst. The exposed muffler temperatures are nominally equivalent.

Table 7-5: Class II Safety FMEA Items

Class II Safety FMEA Items

Ref. No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Note
1	Intake Air Filter	Degradation or tear of filter element, wrong filter or dirty or missing filter.	richer mixture	backfire	fire or burn	1_Safety	10	2	20	20	10	2	0	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. The occurrence is held the same for Phase 2 and 3 in this case since Class II, Phase 2 products are already judged to have a relatively low occurrence of backfire due to intake filter issues.
2	Intake Air Filter	Degradation or tear of filter element, wrong filter or dirty or missing filter.	leaner mixture	hotter exhaust	fire or burn	1_Safety	10	3	30	30	10	3	0	The rankings are the same with or without a catalyst because there will be no increase in fire or burn risk with the application of a properly designed catalyst. The effect could be mitigated by the presence of a thermal switch.
3	Carburetor System	Restriction in fuel passages, wrong jets in production, or choke stuck open, or production variability. Fuel injection system fuel pump or fuel pressure regulator failure. Fuel filter or injector restriction. Injector wiring connection degraded. MAP, ECM, or O2 sensor failure.	leaner mixture	higher temperature in engine and Catalyst	fire or burn	1_Safety	10	3	30	30	10	3	0	The rankings are the same with or without a catalyst. Any effect that the catalyst might have on temperature level is offset by the expected improvements in air cooling of the manifold system on Phase 3 products. If the change in temperature is significant the effect could be mitigated by the presence of a thermal switch.

Class II Safety FMEA Items

Ref. No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Note
4	Carburetor System	Float breaks, debris in float needle, or wrong jets in production, choke stuck closed, or production variability. Fuel injection fuel system fuel pressure regulator failure. Fuel injector stuck open. MAP, ECM, O2 sensor failure.	richer mixture	backfire	fire or burn	1_Safety	10	4	40	30	10	3	10	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. That fact drives a reduction in the Occurrence ranking.
5	Carburetor System	gasket failure, or needle valve stuck open, or fuel pump / regulator leak	leakage of fuel to mower deck, air filter or elsewhere (i.e. out of air filter)	fuel ignites	fire or burn	1_Safety	10	2	20	20	10	2	0	The rankings are the same with or without a catalyst because exposed muffler temperatures are nominally equivalent. Fuel can be ignited by hot surfaces or the ignition system.
6	Carburetor System	gasket failure, or needle valve stuck open, or fuel pump / regulator leak	leakage of fuel to mower deck, air filter or elsewhere (i.e. out of air filter)	fuel puddles	fire or burn	1_Safety	10	3	30	30	10	3	0	The rankings are the same with or without a catalyst because exposed muffler surfaces have been shown to be nominally equivalent in Phase 2 (no catalyst) and Phase 3 (catalyzed) prototype systems.
7	Carburetor System	ECM failure, solenoid return spring breakage causes fuel cutoff solenoid open failure	fuel flow into and from engine	fuel puddles	fire or burn	1_Safety	10	4	40	40	10	4	0	The rankings are the same with or without a catalyst.

Class II Safety FMEA Items

Ref. No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Note
8	Governor	None	malfunctioning governor	open governor causes engine overspeed	catastrophic failure (potential injury due to flying parts)	1_Safety	9	2	18	18	9	2	0	Engine failure caused by overspeed. The rankings are the same with or without a catalyst.
9	Intake Manifold	Crack or leak in manifold	leaner mixture	engine, exhaust system and catalyst run hotter	fire or burn	1_Safety	10	4	40	40	10	4	0	The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
10	Intake Manifold	Intake manifold leak causes MAP to read higher pressure	richer mixture	backfire	fire or burn	1_Safety	10	3	30	30	10	3	0	The failure relates to fuel Injected engines. EPA demonstrated that the backfire impact was reduced with the addition of a properly designed catalyzed muffler system for Class I. However, since the design quality of the Class II equipment mufflers is very good on Phase 2, the impact of adding the catalyst is minimal.
11	Block	Higher thermal load	higher engine temperatures	engine failure (internal component seizure, broken valve or spring, excess wear)	catastrophic failure (potential injury due to flying parts)	1_Safety	9	3	27	27	9	3	0	Engine failure caused by excessive temperatures. The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
12	Block	Higher thermal load	higher engine temperatures	engine failure (internal component seizure, broken valve or spring, excess wear)	fire or burn	1_Safety	10	3	30	30	10	3	0	Engine failure can result in contact with hot metal or fluids. The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
13	Exhaust Manifold	None	cracked muffler, manifold or failed gasket	exhaust leak	fire or burn	1_Safety	10	4	40	30	10	3	10	The lower Phase 3 occurrence is due to the Phase 3 definition of improved exhaust system design.
14	Exhaust Manifold	Debris accumulation	reduction in engine cooling / increased muffler temperatures	ignition of debris adjacent to muffler	fire	1_Safety	10	3	30	20	10	2	10	The lower occurrence for the Phase 3 is due to the improvement of the air ducting for cooling and control of debris accumulation.

Class II Safety FMEA Items

Ref. No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Note
15	Exhaust Manifold	None	removal or mechanical failure	loss of muffler shroud	fire or burn	1_Safety	10	3	30	20	10	2	10	The lower occurrence for the Phase 3 is due to the improvement of the air ducting design for cooling and shroud design.
16	Catalyst	Manufacturing, supplier or installation problem	incorrect or improperly installed catalyst	increased catalyst performance	fire or burn	1_Safety	1	1	1	20	10	2	-19	The Phase 2 ranking is low by definition, since Phase 2 does not have a catalyst. For Phase 3, the severity ranks high due to the potential safety impact. The effect could be mitigated by the presence of a thermal switch.
17	Cooling System	None	plugging of cooling passages due to debris	reduction of engine cooling	burn risk	1_Safety	9	4	36	27	9	3	9	The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
18	Cooling System	None	cooling system shroud failed	loss of cooling	burn risk	1_Safety	9	2	18	18	9	2	0	The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
19	Ignition System	None	plug bad, short in plug wire, failed coil, loose flywheel, magneto, ignition module failure	weak or intermittent spark, or loss of ignition in one of two cylinders (misfire)	excessive muffler or catalyst temperatures and increased burn risk	1_Safety	9	3	27	27	9	3	0	The rankings are the same with or without a catalyst. The effect could be mitigated by the presence of a thermal switch.
20	Ignition System	bad plug, short in plug wire, failed coil, loose flywheel, magneto	loss of spark	Backfire (misfire)	fire or burn	1_Safety	10	4	40	30	10	3	10	In this scenario, the backfire is of such intensity that it can cause a fire or burn. EPA demonstrated that the backfire incidence was significantly reduced with the addition of a properly designed catalyzed muffler system. That fact drives a reduction in the Occurrence ranking.
21	Fuel Tank	None	leak of tank or line	fuel puddles, or sprays	fire or burn	1_Safety	10	3	30	20	10	2	10	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence
22	Fuel Tank	None	leak of tank or line	fuel puddles, or sprays	operator fuel exposure	1_Safety	9	3	27	18	9	2	9	The rankings are the same with or without a catalyst.
23	Fuel Tank	Equipment tip over, material failure, component failure	leak of tank or line	fuel contacts hot component	fire or burn	1_Safety	10	3	30	20	10	2	10	By definition of the Phase 3 product, the improved design features for Phase 3 is expected to result in a slight reduction in Occurrence. The evaporative emission controls will reduce leak occurrence

Class II Safety FMEA Items

Ref. No.	Item	Potential Cause (Contributing)	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev Ph2	Occur Ph 2	RPN Ph 2	RPN Ph 3	Sev Ph 3	Occur Ph 3	RPN Delta (Ph 2 vs Ph 3)	Note
24	Fuel Tank	High muffler or catalyst temperatures near fuel tank	fuel tank or line melted	fuel puddles or sprays	fire or burn	1_Safety	10	2	20	20	10	2	0	The rankings are the same with or without a catalyst.
25	Fuel Tank	High muffler or catalyst temperatures near fuel tank	fuel tank or line melted	fuel puddles or sprays	operator fuel exposure	1_Safety	9	2	18	18	9	2	0	The rankings are the same with or without a catalyst.
26	Fuel Tank	High muffler or catalyst temperatures near fuel tank	fuel tank or line melted	fuel contacts hot component	fire or burn	1_Safety	10	2	20	20	10	2	0	The rankings are the same with or without a catalyst.

Table 7-6: Refueling Process FMEA

Refueling Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
1	Shut off engine	failed to shut engine off	engine running	risk of refueling while engine running and a potential of a fire or burn	1_Safety	9	2	18	No difference between Phase 2 and Phase 3 expected. Thermal images indicate that at idle operation the maximum surface temperatures are comparable for Phase 2 and Phase 3 designs.
2	Open mower cap	overpressure of fuel tank	spillage (hot fuel, full tank, pressurized tank - i.e. vent blocked)	operator contact w/ fuel	1_Safety	9	2	18	A safety concern, but no significant difference between Phase 2 and Phase 3 expected. (Phase 3 tank venting could be a slight improvement)
3	Open mower cap	overpressure of fuel tank		spillage onto hot surfaces and a potential of a fire or burn	1_Safety	9	2	18	A safety concern, but no significant difference between Phase 2 and Phase 3 expected. (Phase 3 tank venting could be a slight improvement)
4	Open mower cap	overpressure of fuel tank		fire	1_Safety	10	2	20	A safety concern, but no significant difference between Phase 2 and Phase 3 expected. (Phase 3 tank venting could be a slight improvement)
5	Remove fuel can cap	operator behavior	Fail to open vent	fuel spillage	1_Safety	9	4	36	A safety concern, but no difference between Phase 2 and Phase 3 expected.
6	Remove fuel can cap	hot fuel and high pressure(high temperature storage, heating from sunlight)	fuel spray upon opening cap/vent	operator contact w/ fuel	1_Safety	9	2	18	A safety concern, but no difference between Phase 2 and Phase 3 expected.
7	Remove fuel can cap	hot fuel and high pressure(high temperature storage, heating from sunlight)		spillage	1_Safety	9	2	18	A safety concern, but no difference between Phase 2 and Phase 3 expected.
8	Remove fuel can cap	operator behavior		spillage	1_Safety	9	4	36	A safety concern, but no difference between Phase 2 and Phase 3 expected.
9	Remove fuel can cap	operator behavior		vapor released from can	1_Safety	9	4	36	A safety concern, but no difference between Phase 2 and Phase 3 expected.

Refueling Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
10	pick up can and pour	fuel spill	fuel puddle on equipment	fuel fire	1_Safety	10	4	40	A safety concern, but no difference between Phase 2 and Phase 3 expected.
11	pick up can and pour	fuel spill	fuel spill into fan inlet	fuel fire	1_Safety	10	4	40	A safety concern, but no difference between Phase 2 and Phase 3 expected.
12	pick up can and pour	fuel spill	fuel over the cowling and makes contact with a hot exhaust system component	fuel fire	1_Safety	10	4	40	A safety concern, but effectively no difference between Phase 2 and Phase 3 expected. Thermal imaging cross-validation studies indicated that "…the application of a catalyst to a small gasoline engine does not increase, and can actually lower, exhaust system surface temperatures…"
13	pick up can and pour	fuel spill	spill on operator and/or bystander	fuel exposure	1_Safety	9	4	36	A safety concern, but no difference between Phase 2 and Phase 3 expected.
14	pick up can and pour	fuel spill		fuel fire and burn	1_Safety	10	4	40	A safety concern, but no difference between Phase 2 and Phase 3 expected.
15	pick up can and pour	fuel spill	spillage on surrounding areas	fuel fire and burn	1_Safety	10	4	40	A safety concern, but no difference between Phase 2 and Phase 3 expected.
16	pick up can and pour	fuel spill		creates combustible material	1_Safety	9	4	36	A safety concern, but no difference between Phase 2 and Phase 3 expected.
17	pick up can and pour	material failure	gas can cracks	fuel spill and potential of fire or burn	1_Safety	9	3	27	A safety concern, but no difference between Phase 2 and Phase 3 expected.
18	pick up can and pour	engine running	refuel while running	spill fuel	1_Safety	9	2	18	A safety concern, but no difference between Phase 2 and Phase 3 expected.
19	pick up can and pour	engine running		fuel vapor ignites	1_Safety	10	2	20	A safety concern, but no difference between Phase 2 and Phase 3 expected.
20	pick up can and pour	static charge	spark	fire or explosion	1_Safety	10	2	20	A safety concern, but no difference between Phase 2 and Phase 3 expected.

Refueling Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
21	pick up can and pour	gas cap on can is not secure	spillage on surrounding areas	fire or burn	1_Safety	10	2	20	A safety concern, but no difference between Phase 2 and Phase 3 expected.
22	Recap the Mower Tank	failure to recap mower tank	fuel spillage or vapor release onto equipment or operator during operation	fire	1_Safety	10	3	30	A safety concern, but no difference between Phase 2 and Phase 3 expected.
23	Recap the Mower Tank	failure to recap mower tank		fuel exposure	1_Safety	9	3	27	A safety concern, but no difference between Phase 2 and Phase 3 expected.
24	Restart	fuel on the equipment	ignition component failure	fire or burn	1_Safety	10	2	20	A safety concern, but no difference between Phase 2 and Phase 3 expected.
25	Restart	fuel or debris left on the equipment	hot surfaces ignites	fire or burn	1_Safety	10	2	20	A safety concern, but no difference between Phase 2 and Phase 3 expected.

Table 7-7: Shutdown and Storage Process FMEA

Shutdown and Storage Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
1	Engine Shut Down	ignition cut off and engine brake fail (and engine does not shut off)	engine left running, and operator may pull plug wire to stop	high surface temperatures, and risk of fuel ignition from high voltage spark and risk of shock	1_Safety	9	2	18	No difference between Phase 2 and Phase 3 expected
2	Engine Shut Down	engine won't stop and operator goes for help	untended operation	bystander gets injured by burn	1_Safety	10	2	20	No difference between Phase 2 and Phase 3 expected
3	Engine Shut Down	engine won't stop and operator goes for help		debris fire	1_Safety	10	2	20	No difference between Phase 2 and Phase 3 expected
4	Engine Shut Down	engine won't stop and operator pulls plug wire	risk of fuel ignition due to high voltage spark	fire or burn	1_Safety	10	2	20	No difference between Phase 2 and Phase 3 expected
5	Engine Shut Down	engine won't stop and operator pulls plug wire	operator contacts hot component	burn	1_Safety	10	2	20	No difference between Phase 2 and Phase 3 expected
6	Equipment Storage	cover with tarp while engine hot (any material)	tarp ignites	fire ignites adjacent materials	1_Safety	10	2	20	Tarp ignites and fire could spread. No impact due to addition of a catalyst.
7	Equipment Storage	cover with tarp while engine hot (any material)		fire damages equipment	1_Safety	10	2	20	Tarp ignites and fire could spread. No impact due to addition of a catalyst.
8	Equipment Storage	store in or near garage or shed when engine hot	equipment ignites combustible material	structural fire	1_Safety	10	1	10	Surrounding material could ignite. No impact due to addition of a catalyst. Data available does not support a higher occurrence ranking.
9	Equipment Storage	store in or near garage or shed when engine hot	water heater pilot light ignites gasoline vapor from leak, spill or refueling	structural fire	1_Safety	10	1	10	Gas vapor could ignite. No impact due to addition of a catalyst. Data available does not support a higher occurrence ranking.
10	Equipment Storage	store in or near garage or shed when engine hot	Spilled fuel or debris on mower deck ignites	Equipment or structural fire	1_Safety	10	1	10	Debris on the mower deck could ignite. No impact due to addition of a catalyst. Data available does not support a higher occurrence ranking.

Shutdown and Storage Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
11	Equipment Storage	store in or near garage or shed when engine hot	operator and/or bystander contacts hot component	burn	1_Safety	10	2	20	No impact due to addition of a catalyst.
12	Equipment Storage	park equipment on combustible debris	debris ignites	debris fire	1_Safety	10	2	20	Surrounding material could ignite. No impact due to addition of a catalyst.
13	Equipment Storage	park equipment on combustible debris		structural fire	1_Safety	10	2	20	Surrounding material could ignite. No impact due to addition of a catalyst.
14	Equipment Storage	park equipment on combustible debris		bystander gets injured by burn	1_Safety	10	2	20	No impact due to addition of a catalyst.
15	Equipment Storage	park equipment on combustible debris		fire damages equipment	1_Safety	10	2	20	Surrounding material could ignite. No impact due to addition of a catalyst.

Table 7-8: Maintenance Process FMEA

Maintenance Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
1	Cleaning Equipment	Tip equipment to clean underneath	spill fuel or oil	fire	1_Safety	10	8	80	Vapor control requirements will reduce occurrence with Phase 3 product to 7 and the RPN to 70.
2	Cleaning Equipment	Tip equipment to clean underneath		operator exposure to fuel or oil	1_Safety	9	8	72	Vapor control requirements will reduce occurrence with Phase 3 product to 7 and the RPN to 63.
3	Cleaning Equipment	maintenance or cleaning while the equipment is hot	contact with hot part	burn	1_Safety	10	6	60	No difference between Phase 2 and Phase 3 expected
4	Change Oil / Filter	Improper maintenance	spill oil	operator exposure to oil	1_Safety	9	9	81	No difference between Phase 2 and Phase 3 expected
5	Change Oil / Filter	maintenance or cleaning while the equipment is hot	contact with hot part	burn	1_Safety	10	6	60	No difference between Phase 2 and Phase 3 expected
6	Change Oil / Filter	Tip equipment for maintenance	spill fuel or oil	fire	1_Safety	10	8	80	Vapor control requirements will reduce occurrence with Phase 3 product to 7 and the RPN to 70.
7	Change Oil / Filter	Tip equipment for maintenance		operator exposure to fuel or oil	1_Safety	9	8	72	Vapor control requirements will reduce occurrence with Phase 3 product to 7 and the RPN to 63.
8	Change Air Filter	maintenance or cleaning while the equipment is hot	contact with hot part	burn	1_Safety	10	6	60	No difference between Phase 2 and Phase 3 expected
9	Change Spark Plug	maintenance or cleaning while the equipment is hot	contact with hot part	burn	1_Safety	10	6	60	No difference between Phase 2 and Phase 3 expected
10	Change Spark Plug	testing for spark	spark ignites fuel	fire	1_Safety	10	3	30	No difference between Phase 2 and Phase 3 expected
11	Sharpen Blade	tipping equipment for blade access	equipment falls	personnel injury	1_Safety	10	5	50	No difference between Phase 2 and Phase 3 expected
12	Sharpen Blade	tipping equipment for blade access	spill fuel or oil	fire	1_Safety	10	8	80	Vapor control requirements will reduce occurrence with Phase 3 product to 7 and the RPN to 70.

Maintenance Process FMEA

Ref. Item No.	Process Function	Potential Cause (Primary)	Potential Failure Modes	Potential Effect(s) of Failure	Classification of Effect	Sev	Occur	R.P.N.	Notes
13	Sharpen Blade	Improper reassembly	spill fuel or oil	personnel injury	1_Safety	10	1	10	No difference between Phase 2 and Phase 3 expected
14	Replace Drive Belt	wrong belt installed	belt slips or does not engage	belt fire / debris fire	1_Safety	10	4	40	No difference between Phase 2 and Phase 3 expected
15	Replace Drive Belt	belt installed incorrectly	belt slips or does not engage	belt fire / debris fire	1_Safety	10	3	30	No difference between Phase 2 and Phase 3 expected
16	Replace Drive Belt	maintenance or cleaning while the equipment is hot	contact with hot part	burn	1_Safety	10	6	60	No difference between Phase 2 and Phase 3 expected

8. Conclusions – Impact of Phase 3 Exhaust Standards on Class I and Class II NHH Engines

In this chapter, EPA draws conclusions based upon:

1. the results of laboratory testing conducted with EPA prototypes of engines with Phase 3 exhaust emissions control systems,

2. the results of laboratory testing conducted with current Phase 2 engines, and

3. the results of the FMEA for each of the key scenarios used to evaluate the incremental risk associated with advanced emission control technology for NHH engines and equipment.

In all cases, based on the data presented in this report, EPA concludes that the catalyst-based Phase 3 standard under consideration poses no incremental increase in the risk of fire or burn for Class I and Class II NHH engines.

SCENARIO 1: CONTACT BURNS

<u>Scenario Description: Thermal burns due to inadvertent contact with hot surface on engine or equipment.</u>

Potential Causes:

a. muffler surface temperature increases due to debris inhibiting flow of cooling air

b. higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine

c. muffler temperature increase due to air-to-fuel ratio enleanment caused by calibration drift over time, fuel system problems or air filter element mal-maintenance

d. exhaust gas leaks increase surface temperatures

<u>Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:</u>

a. *Muffler surface temperature increases due to debris inhibiting flow of cooling air*: Engines equipped with catalyst-mufflers showed no greater propensity to trap debris than those equipped with OEM mufflers, even during operation in high-debris environments in the field. Both laboratory and field testing showed that properly designed catalyst-mufflers could achieve comparable, or even cooler, surface temperatures relative to today's OEM muffler designs. EPA did find evidence of cooling air being blocked by debris during field testing for some engine designs, regardless of exhaust system configuration (see figure 6-36). A partially blocked cooling system could potentially limit the amount of cooling air available for forced convective cooling of the exhaust system, and this could occur whether or not the engine is equipped with a catalyst. Engines 244 and 245 in Class I and all of the Class II engines tested were designed with coarse screens on the inlet to the cooling fan. Engines with properly designed cooling fan air-inlet screens had minimal or no issues regarding debris ingestion and blockages within the engine cooling system. Debris build-up on muffler surfaces did not occur on engines equipped with air-shrouding for muffler or catalyst-muffler cooling. Properly designed systems were capable of grass cutting operations to near the end of useful life with minimal build-up of debris either within the cooling system or on exhaust system surfaces (engines 231, 232, 233, 244, 245, 251). These grass cutting operations included high-debris conditions that led to nearly complete blockage of the cooling systems on engines 246, 248, 249 and 259. Retrofitting the engines with a screen near the air-inlet to the cooling fan resolved the debris-blockage issue.

b. *Higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine*: EPA laboratory testing and field testing clearly indicate that comparable, or even cooler, surface temperatures can be achieved for properly designed catalyst-mufflers relative to today's OEM mufflers (see Chapter 6). Most Phase 2-compliant engines already have sufficient cooling-air capacity to manage heat rejection from properly designed catalyst-mufflers, and cooling system designs will be carried or improved for Phase 3 engines. Proper catalyst design for minimizing heat load includes the use of catalyst designs that minimize of CO oxidation through careful selection of catalyst size, washcoating composition and PGM loading. Comparisons of surface temperatures between OEM muffler and catalyst-muffler configurations for a broad range of engine families and operational conditions are presented within Chapter 6.

c. *Muffler temperature increase due to air-to-fuel ratio enleanment caused by calibration drift over time, fuel system problems or air filter element mal-maintenance*: Conditions of richer and leaner air-to-fuel ratios, as well as little to no change in air-to-fuel ratio, have been observed on the engines EPA has tested as they have accumulated hours, and can occur whether the engine is equipped with a catalyst-muffler or with current OEM muffler designs. Leaner air-to-fuel ratios tend to lead to increased exhaust gas temperatures. While exhaust temperatures would increase regardless of the presence of a catalyst, the concern is that excessive exhaust system surface temperatures would occur if the engine operated near or lean of stoichiometry due to the increased availability of oxygen in the exhaust for CO oxidation over the catalyst.

   The only induction system problem that EPA has observed as a consistent cause of lean operation at high hours has been a failure of the seal between the carburetor and intake manifold with one particular family of Class I engine. This particular engine family uses a plastic, tubular intake manifold design without a manifold flange onto which the carburetor can directly mount. Instead, the carburetor seals to the manifold tube by deforming an O-ring located between the carburetor, a carburetor support, and the tube. With this design, a flat-spot often wears onto the O-ring over time due to engine vibration and insufficient support of the weight of the carburetor, resulting in an air leak into the induction system that bypasses the carburetor and causes lean operation. This was a common occurrence during field aging of lawn mower engines in southeast Michigan with three out of four engines from the same engine family as engine 258 having an intake manifold O-ring failure and subsequent induction leak with lean operation. Some of the engines that had intake-manifold gasket failures in the field were tested by EPA, and then sent to an independent laboratory for tear-down and inspection. The engines were at or close to catastrophic mechanical failure (complete inoperability), and in one case the engine could not be started and run on the dynamometer for testing. These engines had:

   1. Greatly reduced power output (up to 40% lower)
   2. Very poor load pickup
   3. Failed head gaskets
   4. Cylinder head temperatures exceeding 300 °C and oil temperatures of 180 to 200 °C at high loads
   5. Greatly increased oil consumption, due to cylinder bore distortion and loss of oil viscosity at high temperatures
   6. Visible smoke coming from the exhaust (see Figure 8-1)

   In the event of an induction system failure resulting in a severe manifold air leak and lean-of-stoichiometric operation, an increased catalyst exotherm would occur as long as the catalyst is active. Net lean operation with an air-cooled engine at above moderate load conditions would also result in engine damage, and would likely result in deactivation of the catalyst from both thermal sintering and oil-poisoning. In extreme cases, lean operation and high oil consumption may lead to substrate failure or plugging of the monolith which may result in engine inoperability.

Figure 8-1: Smoke plume at idle from Class I engine with failed intake manifold and head gasket.

Use of a proper intake manifold design with positive sealing through a flat intake manifold flange, along with proper mechanical support of the mass of the carburetor minimizes the likelihood of lean-drift of the air-to-fuel ratio over time. Other engine families tested by EPA that used more typical flat-flange-mounting systems on their intake manifolds or, in some cases, direct mounting of a side-draft carburetor to the intake port with no manifold, together with robust carburetor support did not exhibit any significant trend towards lean operation at high hours.

Catalyst deactivation is an emissions compliance issue, engine manufacturers will need to use robust intake manifold designs and carburetor supports in order to comply with the Phase 3 emissions regulations to the end of the engines' useful life. Such designs should reduce or eliminate the occurrence of lean air-to-fuel ratio drift, and should improve both the safety and the durability of Phase 3 engines relative to today's Phase 1 and Phase 2 engines. Another alternative for walk-behind lawn mowers would be to entirely prevent operation of a malfunctioning engine via the use of a low cost (<$1.00), self-resetting bimetal-disk thermal switch to shut down the engine's ignition system if a pre-set temperature is exceeded. Bimetal devices are already commonly used on Class I lawn mower engines to provide automatic choke activation, and are non-contact devices that are mounted directly behind the muffler to sense exhaust heat. Noncontact bimetal shut-off switches are used in a wide variety of consumer products, including portable hair-driers, irons, battery-electric lawn mowers, home water heaters and clothes driers.

The impact of air filter mal-maintenance on emissions and air-to-fuel ratio has been significantly reduced since the advent of the Phase 2 emission standards in the US. The majority of carburetors used with Phase 2 engines are equipped with float bowl venting that provides compensation for air-filter mal-maintenance. Thus changes in carburetor air-inlet restriction are already largely compensated for by design.

d. *Exhaust system leaks*: The hypothesis is that an exhaust leak would allow significant air entrainment into the exhaust system upstream of the catalyst, leading to increased CO oxidation and increased catalyst-muffler surface temperatures. The layout of existing Class I and Class II exhaust systems would make the occurrence of this phenomenon extremely unlikely. The relatively close coupled exhaust systems used by Class I and Class II engines along with the exhaust restriction imposed by the muffler and catalyst would cause exhaust leaks out of the exhaust system, but would limit ambient air leakage into the exhaust system to a negligible level since the pressure pulsations in the exhaust are entirely or nearly entirely at a higher pressure than ambient.

Controlled "leakage" of air into exhaust systems is used as a method of providing secondary air for exhaust catalyst systems. Examples include the stamped venturi used by European catalyst-mufflers on Class I engines (see figure 5-1) and the check-valve pulse-air systems used with some motorcycle catalyst systems and used by automobiles in the 1980s and early 1990s. It is highly unlikely that an exhaust leak would occur in a manner that would produce the exact shape and exhaust flow restriction necessary for venturi induction of air into the exhaust.

> Pulse-air systems rely on exhaust gas pulsation to just below ambient pressure to draw air into the exhaust through a check-valve. Such systems rely on the fact that exhaust traveling through a long pipe has inertia and the flow is compressible. Between exhaust valve events, the inertia of the exhaust gases can create temporary conditions at which the exhaust gases are below ambient pressure, allowing ambient air to be entrained into the exhaust system. While the pulse-air phenomenon has been used successfully with catalyst systems in numerous automotive and motorcycle applications, attempts to apply pulse-air systems to Class I and Class II engines have not been successful. Class I lawn mower mufflers are most often mounted directly to the exhaust port, although some are mounted up to 4-inches downstream of the exhaust port. Class II lawn tractor mufflers are mounted approximately 8-inches to 2-feet downstream of the exhaust port. EPA attempted to apply check-valve pulse air systems to both Class I and Class II engines during early development of exhaust catalyst systems in support of the Phase 3 rule. With such close coupling of the exhaust system, the inertia of the exhaust gases traveling from the exhaust port and the exhaust system upstream of the catalyst-muffler resulted in exhaust pressure that did not fall below ambient pressure between exhaust valve closing and opening events, and thus there was no net change in exhaust stoichiometry. Similarly, EPA expects that leakage in these systems would obey physics and result in exhaust gases traveling from the higher pressures found within the exhaust system to the lower pressures found in the ambient without any significant amount of air moving in the opposite direction.

Temperatures above the human skin burn threshold exist with current production OEM mufflers under a broad range of normal operating conditions. Proper design and layout of the exhaust system can minimize occurrences of touch-burns regardless of whether or not the exhaust system incorporates a catalyst or if a system fault occurs. EPA demonstrated similar or cooler operating temperatures for properly-designed catalyst-mufflers compared to today’s OEM mufflers (see Chapter 6). Catalyst-mufflers equipped with air shrouds and exhaust ejectors in some cases resulted in systems that were significantly cooler than many current OEM muffler designs.

Conclusions Based on FMEA of Burn Safety

The potential for increased temperature which could increase thermal burns was assessed in various engine subsystems and processes within the FMEA. In the FMEA protocol, if the effect of the potential failure was burn or increased burn risk the item was given a severity classification of 9. There were 58 items in the 5 FMEAs which indicated burn or increased burn risk as the potential effect of failure. As can be seen in Table 8-1 below, there was not a significant change in risk probability for burns in going from a Phase 2 engine to a properly designed Phase 3 system. Overall, 17 items in the five FMEAs indicated the potential for a small improvement in risk probability, two indicated the potential for a small degradation, and 39 indicated no change.

Table 8-1: Burns Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	Number of Items with Burn as the Potential Effect of Failure	Number with Potential Improvement	Number with No Change	Number with Potential Degradation*
Design				
Class I:	19	10	8	1
Class II:	21	7	13	1
Process				
Refueling:	8	0	8	0
Shutdown/Storage:	5	0	5	0
Maintenance:	5	0	5	0

* These two items are discussed in Chapter 7, section G.

SCENARIO 2: DEBRIS FIRE

Scenario Description: Grass and leaf debris on engine/ equipment

Potential Causes

a. muffler surface temperature increases due to debris inhibiting flow of cooling air, debris trapped in tight areas blocks air flow, dries out and heats up

b. higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine

c. muffler temperature increase due to air-to-fuel ratio enleanment caused by calibration drift over time, fuel system problems or air filter element mal-maintenance

d. exhaust gas leaks increase surface temperatures

e. misfueling: use of highly oxygenated fuel such as E85

Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:

a. *Muffler temperature increases due to debris inhibiting flow of cooling air, debris trapped in tight areas blocks air flow, dries out and heats up*: As mentioned in the previous section on touch burns, engines equipped with properly-designed catalyst-mufflers have no greater propensity to trap debris than those equipped with OEM mufflers, and have successfully operated to full useful life in the field under conditions that included high-debris environments. Both laboratory and field testing have shown that properly designed catalyst-mufflers can achieve comparable, or even cooler, surface temperatures relative to today's OEM muffler designs. The combination of air shrouding and the use of exhaust ejectors can be expected to provide significant improvements in prevention of debris build-up and debris ignition by lowering surface temperatures, lowering exhaust gas outlet temperatures, and improving debris clearance over hot exhaust system surfaces.

b. *Higher temperatures on mower deck or around muffler due to higher radiant heat load from muffler or engine or exhaust system leaks*: As mentioned in the previous section on touch burns, EPA laboratory testing and field testing clearly indicates that comparable, or even cooler, surface temperatures can be achieved for properly designed catalyst-mufflers relative to today’s OEM mufflers (see Chapter 6). Systems using forced-air cooling and exhaust ejectors will actually radiate significantly less onto mower deck surfaces than many existing OEM muffler systems.

c. *Muffler temperature increase due to air-to-fuel ratio enleanment caused by calibration drift over time, air filter element mal-maintenance, or exhaust system leaks*: As mentioned in the previous section on touch burns, air-to-fuel ratio drift can be largely eliminated via moderate improvements to induction system designs. Such improvements will be necessary in order to comply with Phase 3 emission standards at full useful life, and will result in improvements to both engine durability and safety. A low-cost bimetal ignition cut-off switch could also be used for walk-behind lawn mower applications to prevent excessive exhaust system surface temperatures in the event of a system failure causing excessively lean operation.

d. *Exhaust gas leaks increase surface temperatures*: As mentioned in the previous section on touch burns, the exhaust backpressure and layout of Class I and Class II exhaust systems will result in leaks of exhaust gases out of the system, but not air into the system. Thus exhaust leakage cannot appreciably change exhaust stoichiometry, increase CO oxidation, or increase catalyst-muffler temperatures.

e. *Misfueling: use of highly oxygenated fuel such as E85*: Misfueling a Phase 3 Class I or Class II engine with E85 would most likely result in an engine incapable of starting. While E85 is not yet widely available in the U.S., its use is increasing in centrally fueled fleets. The air-to-fuel of ratio of an engine with a similar carburetor calibration to today’s Phase 2 engines would be beyond the lean-flammability limit for sustaining E85 combustion if the tank were completely filled with E85. Misfueling with a lesser amount of E85 would result in anything from no effect at all to lean-misfire or inoperability depending on the ratio with which it is blended with gasoline. A significant degree of lean misfire would rapidly deactivate the catalyst, posing emissions compliance issues but not necessarily safety issues. The carburetor calibration of Phase 3 engines would likely follow current Phase 2 design practice and would allow engine operation on up to 10% ethanol in a gasoline blend. Misfueling beyond 10% ethanol would result in leaner than normal exhaust stoichiometry, but would not necessarily result in higher exhaust gas temperatures. Ethanol has a lower net heat of combustion than gasoline, which effectively would “de-rate” engine power output. Ethanol also can evaporatively cool the intake charge. Both effects would contribute to lowering combustion and exhaust temperatures.

Temperatures capable of causing debris ignition occur under normal operating conditions with current production OEM mufflers. Proper design and layout of the exhaust system are necessary to minimize occurrences of debris ignition regardless of whether or not the exhaust system incorporates a catalyst. EPA demonstrated similar or cooler operating temperatures for properly-designed catalyst-mufflers compared to today’s OEM mufflers. Catalyst-mufflers equipped with air-shrouds and exhaust ejectors in some cases resulted in systems that were significantly cooler than many current OEM muffler designs, and such designs would be expected to decrease, rather than increase, the incidence ignition of debris. Current OEM designs and EPA testing have demonstrated that air-shrouding and forced-air cooling can be incorporated into the exhaust system designs in a manner that not only results in negligible accumulation of debris on hot exhaust system surfaces, but can even assist with clearing debris from hot exhaust system surfaces if proper attention is paid to cooling air velocity and maintaining sufficient gaps within the shrouding around the exhaust system. Testing results for extended idling under dry, high debris conditions show that turf surface temperatures rapidly stabilize (under five minutes) and also demonstrate that turf surface temperatures under and adjacent to lawn tractors equipped with catalyst-muffler can be comparable, or even cooler than, turf surface temperatures underneath and adjacent to current lawn tractors equipped with OEM mufflers (see Chapter 6).

Conclusions Based on FMEA of Debris Fire Safety

The potential for increased temperature which could exacerbate the possibility for debris fires was identified as a potential effect of failure in the Class I and Class II engine subsystems and the refueling and storage/shutdown process FMEAs. In the FMEA protocol, if the effect of the potential failure was fire or increased fire risk the item was given a severity classification of 10 or 9, respectively. There were 23 items in the four FMEAs which indicated fire or increased fire risk related to debris as the potential effect of failure (e.g., not related to fuel or backfire). As can be seen in Table 10-2, below, there were not significant changes in risk probability for debris fires in going from current Phase 2 engines to a properly designed Phase 3 system. Overall, seven items in the four FMEAs indicated the potential for a small improvement in the risk probability, two indicated the potential for a small degradation, and 14 indicated no change.

Table 8-2: Debris Fire Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	**Number of Items with Debris Fire as the Potential Effect of Failure**	**Number with Potential Improvement**	**Number with No Change**	**Number with Potential Degradation***
Design				
Class I:	8	4	3	1
Class II:	8	3	4	1
Process				
Refueling:	1	0	1	0
Shutdown/Storage:	6	0	6	0

* These two items are the same as indicated for contact burn since the potential effect was fire <u>or</u> burn. These two items are discussed in Chapter 7, section G.

SCENARIO 3 FUEL LEAK

<u>Scenario Description: Fires due to fuel leaks on hot surfaces</u>

Potential Causes:

a. faulty fuel tank

b. faulty fuel line or connection

c. tip-over during maintenance

d. tip over in operation

e. faulty carburetor

f. heat affects fuel tank or fuel line integrity

<u>Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:</u>

The faults encountered due to fuel leakage can potentially occur with equal frequency for engines equipped with current OEM muffler designs or with catalyst-mufflers. As indicated above, EPA's testing has shown that properly designed catalyst-muffler systems can achieve comparable, or even cooler, surface temperatures relative to today's OEM muffler designs. Additionally, proper catalyst-muffler thermal management as demonstrated in EPA's test program will result in no significant increase in heat load on fuel system components. Surface temperatures above the auto-ignition temperature for gasoline occur during normal operation for engines equipped with both OEM mufflers and engines equipped with catalyst-mufflers; thus, an equal potential exists for ignition of fuel on hot surfaces if a leak or spillage occurs. Because the Phase 3 regulations address evaporative and running loss emissions, EPA expects that the frequency and severity of fuel leakage and fuel-related fires will be reduced relative to today's Phase 1 and Phase 2 equipment. Compliance with Phase 3 standards will require improvements in tank materials, fuel line materials and fuel line connections, and will reduce the likelihood of failure and/or leakage. Running loss controls on lawn tractors will likely require replacement of front-mounted (engine compartment mounted) fuel tanks with rear-mounted fuel tanks, moving both refueling operations and spillage in the event of turn-over into a location that is further away from hot engine components. Phase 3 compliant venting systems also include cap designs which have the propensity to reduce fuel loss in the event of tipping of equipment either inadvertently or during maintenance. Fuel leakage during maintenance and storage can also be limited to the quantity of fuel in the carburetor float-bowl by equipping lawn mowers and lawn tractors with inexpensive, positive fuel cut-off valves. Fuel cut-off valves are frequently used in consumer lawn-care products.

Conclusions Based on FMEA of Fuel Spills or Leaks

The potential for increased fuel leaks or spills from equipment creating a fire risk was identified as a potential effect of failure in the Class I and Class II engine subsystems and the maintenance process FMEA. In the FMEA protocol, if the effect of the potential failure was fire or increased fire risk the item was given a severity classification of 10 or 9, respectively. There were 16 items in the three FMEAs which indicated fire or increased fire risk related to fuel spill or leak from equipment as the potential effect of failure. As can be seen in Table 8-3, below, there were modest positive changes in risk probability for fuel spill or leak related fires in going from current Phase 2 engines to a properly designed Phase 3 system. Overall, eight items in the three FMEAs indicated the potential for a small improvement in risk probability, none indicated the potential for degradation, and eight indicated no change. The positive changes were related to improved fuel tank designs related to fuel evaporative emission control requirements.

Table 8-3: Fuel Leak or Spill Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	**Number of Items with Fuel-Related Fire as the Potential Effect of Failure**	**Number with Potential Improvement**	**Number with No Change**	**Number with Potential Degradation**
Design				
Class I:	6	3	4	0
Class II:	7	2	5	0
Process				
Maintenance:	3	3	0	0

SCENARIO 4: REFUELING-RELATED

Scenario Description: Fires related to spilled fuel or refueling vapor

Potential Causes:

a. fuel spilled on hot surfaces

b. spilled fuel evaporates or refueling vapors lead to fire indoors

Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:

EPA field test hot-soak data showed that at the manufacturer's specified minimum two minute refueling point after engine shutdown, exhaust system surface temperatures for properly designed catalyst-muffler systems were comparable or cooler than current OEM mufflers. The field tests also showed that exposed surface temperatures rapidly decayed to below the autoignition temperature for gasoline after engine shut-down for all of the lawn tractor and lawn mower configurations tested (see Chapter 6).

Based on CPSC NEISS cases for the five year period of 2000-2004, there was an estimated yearly average of 3,814 emergency room treated thermal burn injuries associated with lawn mowers. Refueling activities accounted for approximately 7% of these injuries. EPA estimates that approximately 1.5 billion refueling events occur per year for lawn and garden equipment. While CPSC NEISS cases involved fires from refueling events, the relative infrequency of refueling fires in comparison with the very large number of refueling events demonstrates that fires from refueling of lawn and garden equipment are relatively infrequent. The surface temperature data indicates that the relative infrequency of refueling fires with this equipment is probably due to surface temperatures rapidly decreasing to below the minimum gasoline surface ignition temperature of approximately 280 °C.[1] This rapid decrease in surface temperatures is comparable equivalent between Phase 2 and expected Phase 3 system configurations (see Chapter 6, section C).

Refueling of lawn mowers or lawn tractors in enclosed areas is hazardous and recommendations against this practice are included in equipment owner's manuals. EPA's field and laboratory data showed that properly designed catalyst-muffler systems can achieve comparable, or even cooler, surface temperatures relative to today's OEM muffler designs. While refueling in an enclosed area is certainly inadvisable under any circumstances, such misuse with a Phase 3 lawn mower or lawn tractor would not pose any additional fire risk beyond the already considerable risk of this practice with current Phase 1 and Phase 2 equipment.

The required changes to fuel systems that will be necessary for compliance with Phase 3 permeation and running loss emissions standards will also reduce the potential for refueling fires for lawn tractors. Relocation of fuel tanks from the engine compartment to the rear of lawn tractors will greatly reduce the likelihood of spilled fuel coming into contact with hot engine surfaces.

Conclusions Based on FMEA of Refueling-Related Safety

The potential for refueling-related fires where the equipment was involved was identified as a potential effect of failure in the refueling process FMEA (see Table 7-6). There were 11 items in the FMEA which indicated fire related to refueling as the potential effect of failure. As can be seen in Table 8-4 below, while fuel evaporative emission controls present the possibility for improvement, overall there was no change in risk probability for refueling-related fires in going from current Phase 2 engines to a properly designed Phase 3 system.

Table 8-4: Refueling Related Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	Number of Items with Refueling-Related Fire as the Potential Effect of Failure	Number with Potential Improvement	Number with No Change	Number with Potential Degradation
Process				
Refueling:	11	0	11	0

SCENARIO 5: STORAGE AND SHUTDOWN

Scenario Description: Equipment or structure fire when equipment left unattended after use.

Potential Causes:

a. ignition of nearby easily combustible materials

b. ignition of fuel vapor by pilot light

c. ignition of dry debris on deck

d. ignition of dry debris in field (lawn tractors)

e. ignition of tarp or other cover thrown over equipment

<u>Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:</u>

Surface temperatures during hot soak conditions following engine shut-down were comparable between equipment tested by EPA with catalyst-mufflers and with OEM mufflers (see Chapter 6). Conditions certainly exist under which combustible materials can be ignited if the equipment is misused, mal-maintained, or stored improperly. The relative frequency of incidences of this sort should be no different for Phase 3 lawn mowers and lawn tractors than is the case for current Phase 1 and Phase 2 equipment. Throwing a tarp over a recently run lawn mower can result in ignition of the tarp regardless of whether or not the lawn mower is equipped with a catalyst-muffler.

While it is certainly inadvisable to store lawn tractors and lawn mowers in enclosures with open flames (e.g., storage of equipment in an attached garage near a water heater or furnace), the frequency of ignition of fuel vapor by pilot lights should be reduced with Phase 3 equipment relative Phase 1 and Phase 2 equipment. This is due to the reduction in volatile organic compound concentrations in the immediate vicinity of the equipment through the use of evaporative emissions controls that comply with the Phase 3 emission standards.

<u>Conclusions Based on FMEA of Shutdown and Storage Safety</u>

The potential for ignition of fuel or other adjacent materials was assessed in the shutdown and storage process FMEA. There were 10 items in the FMEA which indicated fire or increased fire risk related to shutdown and storage (see Table 7-7) as the potential effect of failure. As can be seen in Table 8-5 below, there were no changes in risk probability for storage and shutdown related fires in going from current Phase 2 engines to a properly designed Phase 3 system. This is the case because the hot surface cool down profiles for Phase 2 equipment and properly designed Phase 3 equipment are comparable.

Table 8-5: Shutdown and Storage FMEA Safety Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	**Number of Items with Shutdown/Storage Fire as the Potential Effect of Failure**	**Number with Potential Improvement**	**Number with No Change**	**Number with Potential Degradation**
Process				
Shutdown/Storage:	10	0	10	0

SCENARIO 6: IGNITION MISFIRE

Scenario Description: Engine malfunction which results in an ignitable mixture of unburnt fuel and air in the muffler.

Potential Causes:

a. misfire caused by partial failure in ignition system (single cylinder engines)

b. misfire caused by failure in ignition system, particularly complete failure of ignition for one cylinder (2 cylinder V-twin engines)

c. after-fire/backfire caused by engine run on after ignition shut-down due to failure of the engine flywheel brake or carburetor fuel-cut solenoid

Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:

Ignition misfire can rapidly result in catalyst deactivation. Because of this, EPA predicts that ignition system improvements that include use of higher output ignition coils and higher-quality ignition wires will be necessary to ensure compliance with the Phase 3 emission standards. These improvements will decrease the incidence of ignition misfire relative to Class 1 and Class 2 equipment. Still, of the potential failure modes that can occur, ignition misfire is the condition of most concern with regards to the use of catalyst-mufflers with Class I lawn mowers and Class II lawn tractors. This is the only condition that has been identified that provides both excess fuel and excess air simultaneously to exhaust system internal surfaces in a proportion that can support combustion.

a. *Single-cylinder engine misfire*: The design approach taken by EPA to address ignition misfire with engine 255 was to divide the catalyst volume between locations upstream and downstream of secondary air entrainment (“pre-catalyst” and “main catalyst”). These changes improved catalyst efficiency relative to total catalyst volume, and allowed a reduction in the amount of secondary air used. The reduction in secondary air reduced CO oxidation and reduced surface temperatures during normal operation. This resulted in surface temperatures below that of the OEM muffler during normal operation, and allowed further engineering margin for a temperature increase to occur with the catalyst-muffler during misfire. The pre-catalyst was also optimized for relatively rich operation (similar to 2-stroke catalyst applications) and reduced HC emissions upstream of the entrainment of secondary air both during normal operation and during misfire. This allowed the use of a smaller main catalyst downstream of the secondary air. During misfire, the smaller, space-velocity limited main catalyst was overwhelmed with reactants, thus reducing heat rejection from the main catalyst during misfire. A moderate but manageable increase in temperature was observed for this system, and surface temperatures during misfire were still within 60 °C of normal operating temperatures with the standard muffler. Use of air-shrouding, forced-air cooling of the exhaust and use of an exhaust ejector was more than sufficient to counter the impact of misfire on catalyst-muffler surface temperatures. An alternative approach would be to use a low cost, self-resetting bimetal-disk thermal switch to shut down the engine’s ignition system if high temperatures are encountered near exhaust system surfaces due to a partial ignition system failure.

b. *V-twin ignition misfire*: Conditions exist under which lawn tractors equipped with V-twin engines can operate with one cylinder's ignition system completely deactivated and operate in a manner in which the failure may not be immediately apparent to the operator of the equipment. This is potentially a more hazardous condition than could occur with ignition misfire from a single cylinder engine since a full air and fuel charge from the deactivated engine cylinder can mix with the hot exhaust gases from the active engine cylinder and impinge on hot surfaces within the muffler. A similar degree of misfire with a single cylinder engine would result in engine stalling. One solution would be to divide the exhaust system such that there is one small catalyst substrate for each of the two cylinders of the V-twin. This could be accomplished with two catalyst mufflers, or with a single catalyst muffler with completely separate flow-paths for each cylinder. In the case of full ignition misfire on one cylinder, the exhaust gases would rapidly cool to below the light-off temperature for HC over the catalyst for the section of the catalyst-muffler fed by non-firing cylinder.

c. *After fire caused by engine run-on after shutdown*: EPA testing demonstrated that a properly designed catalyst-muffler can reduce the incidence of after-fire during run-on relative to a current OEM muffler system (see Chapter 6). Design principles for preventing after-fire flame propagation in mufflers are well understood, and can be incorporated into a muffler's baffles and internal passages, and can be combined with spark arresting at the muffler outlet.

Conclusions Based on FMEA of Ignition Misfire

The potential for an increase in misfire-related phenomena to cause an increase in fires or burns was assessed as a potential effect of failure in the Class I and Class II engine subsystems. In the FMEA protocol, if the effect of the potential failure was burn, fire or increased fire risk the item was given a severity classification of 9 or 10. There were four items in the two FMEAs which listed fire or increased burn risk related to misfire as the potential failure mode. As can be seen in Table 8-6, below, there were modest positive changes in risk probability for misfire in going from current Phase 2 engines to a properly designed Phase 3 system. Overall, three items in the two FMEAs indicated the potential for a small improvement, none indicated the potential for degradation, and one indicated no change. The positive changes were related to the expected improvements in the ignition system for a properly designed Phase 3 system.

Table 8-6: Misfire Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	**Number of Items with Misfire Potential Failure Mode**	**Number with Potential Improvement**	**Number with No Change**	**Number with Potential Degradation**
Design				
Class I:	2	2	0	0
Class II:	2	1	1	0

SCENARIO 7: RICH OPERATION

Scenario Description: Fire due to operation with richer than designed air-to-fuel ratio in engine or catalyst.

Potential Causes:

a. fuel system degradation such as faulty carburetor, oil consumption or carburetor deposits

b. faulty or misapplied choke

c. ignition system failure

d. air filter element mal-maintenance

e. debris blocks catalyst venturi

Conclusions Based on EPA Testing of Phase 2 engines and Phase 3 Prototypes:

Based on EPA testing, the impact of richer air-to-fuel ratios appears to be minimal with respect to exhaust surface temperatures (figure 6-35) on both OEM muffler and properly designed catalyst-muffler systems. This is not surprising since during rich operation, exhaust gas oxygen concentrations are low and thus CO oxidation is reduced. Extremely rich air-to-fuel ratios could cause after-fire in the muffler at some conditions. This was not observed in EPA testing at rich air-to-fuel ratio conditions for either the OEM muffler or the catalyst-muffler, or in earlier tests of an engine with a malfunctioning carburetor float valve (engine #1514)[10]. EPA's work with run-on after-fire suggests that with proper design, flame-arresting can be easily incorporated into catalyst-muffler designs to reduce the incidence of after-fire for catalyst-mufflers relative to current OEM mufflers. Overly rich air-to-fuel ratios pose an emissions compliance issue by increasing engine-wear and engine-out emission degradation over time and by reducing catalyst efficiency by partial deactivation of the catalyst through coking of catalyst surfaces. In order to comply with Phase 3 regulations at engine full useful life, it is expected that manufacturers will eliminate the use of manual chokes and switch to the use of either automatic chokes or priming bulbs. This has largely occurred already with Phase 2 Class I engines.

a. *Fuel system degradation*: This would be an emissions compliance issue, but would not result in any difference in safety for Phase 3 equipment relative to existing Phase 1 and Phase 2 equipment.

b. *Faulty or misapplied choke:* The resulting overly-rich air-to-fuel ratios pose an emissions compliance issue by increasing engine-wear and engine-out emission degradation over time, and by reducing catalyst efficiency by partial deactivation of the catalyst through the coking of catalyst surfaces, but would not result in any differences in safety for Phase 3 equipment relative to existing Phase 1 and Phase 2 equipment. In order to comply with Phase 3 regulations at engine full useful life, it is expected that manufactures will eliminate the use of manual chokes and switch to the use of either automatic chokes or priming bulbs. This has largely occurred already with Phase 2 Class I engines.

c. *Ignition system failure:* Ignition system failure is not related to rich operation. As such, it is covered separately under scenario 6.

d. *Air filter element mal-maintenance:* The impact of air-filter mal-maintenance on emissions and air-to-fuel ratio has been significantly reduced since the advent of the Phase 2 emission standards. The majority of carburetors used with Phase 2 engines are equipped with float bowl venting that provides compensation for a degree air-filter mal-maintenance. Thus changes in carburetor air-inlet restriction are already largely compensated for by design. Extreme blockage of the air filter element resulting in rich operation would increase exhaust emissions, but based on EPA test results would not result in any difference in safety for Phase 3 equipment relative to existing Phase 1 and Phase 2 equipment.

e. *Debris blocks catalyst venturi*: The impact of debris blockage of catalyst venturi would be increased emissions and reduced heat rejection at some conditions. While this would pose an emissions compliance issue, EPA would not expect any safety-related impact from venturi air-inlet blockage. The venturi of the European catalyst-muffler design (figure 5-1) is located in a low-debris area in its OEM application. The venturi inlet was similarly located in low debris locations in EPA's applications of this basic design to two different engine families used with four of the engines in the field operations in southwest Tennessee (engines 244, 245, 246, and 248). These systems were operated to near the end of useful life and none experienced any significant degree of venturi blockage.

Conclusions Based on FMEA of Rich Operation

Rich operation was identified as a potential safety concern by one organization. Within the Class I and Class II design FMEAs there were only five situations identified where a rich mixture could potentially create a safety problem. In each case, the potential effect of the failure was backfire. To some degree these problems are redundant with misfire as discussed above. Rich operation can lead to other potential failure effects such hard starting, general degradation of performance, or emissions increases but in no other scenario was there a potential safety issue identified.

Table 8-7: Backfire Safety FMEA Summary – Incremental Change from Phase 2 to Phase 3

FMEA Type	Number of Items with Backfire Potential Failure Mode	Number with Potential Improvement	Number with No Change	Number with Potential Degradation
Design				
Class I:	2	2	0	0
Class II:	3	1	2	0

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[1] American Petroleum Institute, "Ignition Risk of Hydrocarbon Vapors by Hot Surfaces in Open Air", Table 3: Open Air Ignition Tests Under Normal Wind and Convection Current Conditions, API Publication #2216, January 1991.

9. Safety Analysis of Small SI Engine Evaporative Emissions Control Technologies

A. CURRENT TECHNOLOGY

Fuel Evaporative Emissions

EPA intends to propose standards for evaporative emission control requirements for NHH and HH equipment. Evaporative emissions refer to gasoline vapor lost to the atmosphere from a number of mechanisms including:

1. permeation: These emissions occur when fuel vapor works its way through the material used in the fuel system. Permeation occurs most commonly through plastic fuel tanks and rubber fuel hoses.

2. diurnal: These emissions result from temperature changes throughout the day. As the day gets warmer, the fuel temperature increases and the fuel evaporates into the atmosphere. This is sometimes referred to as breathing losses.

3. diffusion: These emissions result from vapor exiting through a vent path to the atmosphere regardless of changes in temperature. This occurs due to the vapor concentration gradient between vapor in the tank or hose and the outside atmosphere.

4. running loss: These emissions are similar to diurnal emissions except that the heating of the fuel is caused by engine operation.

5. refueling: These emissions occur when vapors displaced from the fuel tank escape when fuel is dispensed into the tank.

6. hot soak: These emissions occur from hot fuel cooling after engine shutdown. Traditionally they can emanate from the fuel tank or the carburetor.

7. spillage: These emissions occur when fuel is spilled by the user during refueling events.

The following sections describe the current technological designs for NHH and HH equipment that will be impacted by the potential Phase 3 evaporative emissions standards.

NHH Equipment

NHH equipment refers generally to gasoline-powered equipment that does not require operator support for its operation. It can be free standing, such as a pressure washer or generator, or wheel-based, such as a walk-behind lawnmower, a ride-on mower, or a cultivator. We are considering fuel tank and fuel hose permeation standards, diffusion, and running loss control requirements for NHH equipment.

Fuel tanks for NHH equipment are often mounted on or near the engine. Due to the small size of the tanks and equipment, and to aid in stability in typical Class I applications, the fuel tanks are often mounted directly on the engines. Tank volumes are normally < 0.5 gallon and are made of either metal or high density polyethylene (HDPE). Class I applications normally have only one fuel tank. For Class II equipment, it is more common for fuel tanks to be mounted near the engine on the chassis as opposed to directly on the engine. For example, some ride-on mowers mount the fuel tank in the engine compartment. For equipment with rear-mounted engines it is not uncommon to have the fuel tank in the rear as well. Tank volumes are normally > 1.5 gallons and it is common to have two higher capacity (> 5 gallon) dual tanks on larger commercial equipment. Class II equipment tanks are normally made of injection or blow-molded HDPE or rotomolded cross link polyethylene (XLPE).

Generally, the fuel systems on Class I and Class II equipment have no rollover valves or other mechanisms to prevent fuel from spilling on the engine or equipment when the equipment is tipped on its side or turned over. Some tanks use tortuous venting paths in the fuel caps, which also restrict fuel flow, but others simply use holes in the fuel caps for venting which would also allow fuel to spill out of the tanks at higher flow rates. Fuel tank caps are primarily made of plastic and typically do not have a tether to prevent loss of the cap. Running loss emissions from fuel tank heating during operation are typically vented through the fuel cap.

NHH equipment uses a variety of fuel hose constructions. They may be extruded rubber hose meeting SAE J30R7 requirements or they may use a multi-layer hose such as would meet SAE J30R9. Typical materials used are nitrile rubber, and in some cases, fluoroelastomers.

HH Equipment

HH equipment refers generally to gasoline-powered tools that are supported by the user during operation. This category includes chainsaws, string trimmers, leaf blowers, and other similar equipment. EPA is considering fuel hose and fuel tank permeation standards and diffusion control requirements for HH equipment.

Fuel tanks on HH equipment are typically molded out of either nylon or polyethylene. Most of these tanks are < 0.5 gallons in capacity and in some cases much less. With some equipment, instead of a tank being attached as part of the overall equipment assembly, the fuel tank is structurally integrated into the body of the equipment. This design approach is used in common applications such as chainsaws, hedge trimmers, and brush cutters. This construction helps to provide structural strength to the equipment and results in the fuel tank being molded out of the same material as the rest of the body. In these cases, nylon is typically used due to the favorable heat resistance and stiffness characteristics it offers. The fuel tanks used in HH equipment may either be vented to the atmosphere or they may be sealed. Manufacturers often seal the fuel tanks to prevent spillage during use. This is especially common on tools such as chainsaws where the equipment is regularly turned over during normal use.

HH equipment uses a variety of fuel hose constructions. They may be extruded rubber hose or may be molded into custom forms. Typical materials used are nitrile rubber, polyurethane, polyvinyl chloride, and in some cases, fluoroelastomers. According to the Outdoor Power Equipment Institute, the vast majority of HH equipment has total fuel hose lengths of less than 15 cm.

B. CURRENT SAFETY STANDARDS

The current safety standards for NHH equipment are discussed in Chapter 3. At this point there are no mandatory or general industry consensus standards related to safety practices or standards for fuel tanks or fuel hoses used in NHH or HH equipment. One exception to this is UL 1602 which does present guidelines for the construction of gasoline-powered edgers.

Although industry wide standards are not used, extensive product qualification and durability testing is performed. According to industry sources, manufacturers typically soak tanks at an elevated temperature on various fuels to test for fuel compatibility. In addition, most manufacturers perform impact tests on their fuel tanks. Impact tests vary by manufacturer and can be performed using drop testing, pendulum swung hammers, or sharp point impact. Other procedures that manufacturers have stated that they use for evaluating fuel tank durability include pressure tests and vibration tests.

Most NHH equipment use hose meeting SAE J30 R7 standards. As discussed below, these standards include a long list of durability tests. One engine and equipment manufacturer that does not use hose labeled as SAE J30 R7 stated that they use similar pliability and durability tests as are in the SAE recommended practice. In addition, they test for abrasion resistance and the minimum load required for pulling the hose off of a fitting. They stated that they use the hose pull of load specified in ANSI B71.3. Although this standard is intended for snow throwers, the pull off requirement can be applied to other applications.

HH equipment manufacturers typically use fuel hoses made of polyurethane, nitrile rubber, or polyvinyl chloride. For edgers, the hose must meet a number of durability requirements according to UL 1602. These durability requirements include ultraviolet light exposure, dry heat aging, fuel resistance, and low temperature flexibility. Industry sources have stated that they also perform heat resistance testing and pull off testing on this hose and use the same fuel hose for the rest of their equipment. HH equipment manufacturers also use molded nitrile or fluoroelastomer hoses on some of their equipment. Industry sources stated that they perform a number of durability tests on these hoses as well which include fuel resistance, a pull off load requirement, heat resistance, cold temperature flexibility, and vibration resistance.

ASTM also provides guidance for hose durability testing. ASTM D1149 provides test procedures for determining cracking in the hose that may occur from ozone exposure. ASTM D471 describes test procedures for determining the resistance of rubber products to a number of test fuels. ASTM D380 references these test methods and describes several additional durability tests for fuel hose. These additional tests include tensile strength, elongation, adhesion, pressure tests, low temperature exposure, tension, and hot air aging. One equipment manufacturer specifically stated that they use these test procedures. In addition, all of these ASTM test methods are referenced in SAE J30.

In addition to the above testing, manufacturers often operate the equipment in the field for extended periods of time to evaluate durability. Among other things, these evaluations give manufacturers the ability to evaluate the performance of the fuel tanks, hose, and connections. The use of these durability tests can affect safety in that manufacturers are able to look for defects that may lead to fuel leaks in the field.

Industry sources have also stated that they test for fuel overflow on their NHH equipment. These sources have referenced ANSI standards B17.1 for lawnmowers, B17.3 for snow throwers, and B17.4 for commercial turf equipment. These standards basically require that there be a shield or other method to prevent any fuel overfill during refueling from spilling onto an ignition source such as the muffler or non-insulated electrical wire.

C. IN-USE SAFETY EXPERIENCE

As discussed in earlier chapters, assessing incremental risk requires an understanding of the problems and in-use safety experience with current products. For this analysis we used data from CPSC’s website regarding NHH and HH equipment. The CPSC website publishes Recalls and Product Safety News, where manufacturers, in cooperation with CPSC, voluntarily recall products that pose a safety hazard to consumers. Recall notices published during the period of January 2000 to December 2004 were reviewed. Our analysis focused only on incidences that were relevant to the fuel systems that may be affected by potential Phase 3 emission standards.

NHH Equipment

The in-use safety discussion for NHH equipment in Chapter 3 includes issues related to potential evaporative emission control technology. During the period of January 2000 to December 2004, there were a total of 22 lawn mowers or lawn mower engines recalls due to safety issues related to thermal burn injuries. These 22 recall notices affected approximately 850,000 lawn mower units. In the same time period, CPSC reported 11 recalls for fuel tank leaks and five recalls for fuel line leaks. Chapter 3 presents CPSC Injury/Potential Injury Incident File and In-Depth Investigations related to lawn mower fuel leak incidents.

HH Equipment

In reviewing the CPSC Recall website, EPA reviewed recalls related to gasoline-powered HH equipment such as blowers, trimmers, edgers, chainsaws, augers, and brush cutters. From 2000 to 2004, EPA identified 11 recalls categorized as fire/burn hazards. Of these 11 recall actions, three were associated with potential fuel leakage from hoses, seven were associated with potential fuel leakage from tanks, and one was related to flames in the engine exhaust. These 11 recall actions included more than 80 percent of the HH equipment recalled in that time period.

EPA recognizes that a list of voluntary recalls does not provide details on injuries associated with fires and burns. However, as shown with NHH equipment in Chapter 3, recall notices do provide a good indication of what the safety issues are for a given class of equipment. Based on this, our analysis of incremental risk should focus on fire and burn hazards related to fuel leaks and spills arising from the use of technology to control fuel hose or fuel tank permeation emissions.

D. EMISSION CONTROL SYSTEM DESIGN AND SAFETY

NHH Equipment

We are considering evaporative emission standards for Small SI engines in the Class I and Class II subcategories. These standards include the control of the permeation of fuel vapors through nonmetallic fuel system components, such as rubber fuel hoses and plastic fuel tanks, and the control of fuel vapor vented out of the fuel system. This section discusses the various evaporative emission control approaches under consideration and what impacts these control strategies may have on safety. When evaluating potential safety impacts of evaporative emission control, we considered primarily the chance of a fuel hose or fuel tank liquid leak or a combustible fuel vapor reaching an ignition source, such as a hot exhaust system, when the engine is in use. Thus component durability is a key issue.

Fuel hoses

Most NHH equipment uses rubber hose for delivering gasoline from the fuel tank to the engine. The typical fuel hose construction is a nitrile rubber hose with a protective cover for abrasion resistance. To meet the fuel hose permeation standards under consideration, manufacturers would be able to use this hose construction except that an additional barrier layer would need to be added to minimize permeation fuel through the hose material. A typical barrier material would likely be a fluoroelastomer or fluoroplastic material. Barrier hose constructions are used widely in automotive applications and even on some Class II engines. The lines used today typically meet SAE and ASTM standards; in most cases fuel hose meeting the SAE J30R7 is used. In addition, manufacturers commonly specify minimum loads to pull their fuel hose off of the connecting barbs. One example of a published recommended minimum pull off load is 10 lbs specified in ANSI B71.3.

Fuel hose under the SAE J30 R7 rating must pass a number of tests designed to measure the durability of the hose. These tests include a burst pressure, tensile strength and elongation, dry heat resistance, oil resistance, ozone resistance, kink resistance, and several fuel exposure tests. The fuel resistance tests include repeating most of the above tests after soaking the hose with both ASTM fuel C[f] and a test fuel made up of 85 percent ASTM fuel D blended with 15 percent ethanol. In addition, to test for “sour fuel” resistance, the hose is tested for tensile strength and elongation after being exposed to a test fuel made up of ASTM Fuel B and sufficient t-butyl hydroperoxide to achieve a specified peroxide level. Finally, the hose is tested for permeation on ASTM fuel C. In addition, the SAE requirements include an adhesion test which sets a minimum load required to separate the tube from the protective cover

EPA’s fuel hose permeation requirements must be met using EPA test procedures. However, past testing indicates that many hoses meeting the SAE J30 R9, R11A, or R12 requirements will meet EPA permeation requirements. Hoses meeting R9 or better specifications would also have to meet all other durability requirements associated with the SAE J30 standard as described in the preceding paragraph. Barrier hoses constructed today are generally higher quality hose that also have better temperature resistance than non-barrier hose. For instance, SAE J30 R9 hose must meet a dry heat resistance test based on 150°C heat aging compared to 125°C for R7 hose. According to one hose manufacturer, heat resistance is primarily a function of the cover material rather than the permeation barrier material itself. This should directionally address current concerns related to fuel lines droping under radiant load.

Furthermore, the barrier materials are made of rubber compounds that are resistant to permeation by gasoline, including ethanol blends and oxidized (“sour”) gasoline. This fuel resistance not only protects against chemical attack, but also limits swelling due to the permeation of fuel. By limiting the swelling and contracting (drying) cycles and chemical attacks that may cause the hose to become brittle, the hose may resist cracking as well. Finally, the barrier layers are thin and are not expected to lead to any significant differences in hose flexibility or ability to retain connections within the fuel system. Based on the rigorous nature of the SAE testing requirements and the

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[f] These ASTM fuels are blends of isooctane/toluene: B=70%/30%, C=50%/50%, D=60%/40%.

essentially universal use of hoses meeting SAE specification in NHH applications, we expect no increase in fuel hose leaks associated with the use of low permeation fuel hose relative to current fuel hose. The hose which would be used is commercially available today.

Fuel tanks

Fuel tanks on NHH equipment are usually constructed of HDPE through a blow molding or injection molding process. There are still a few models, some with very high sales, using metal tanks. Some of the larger NHH equipment, such as commercial turf care equipment, uses fuel tanks constructed of XLPE. XLPE is thermoset which means that that a reaction takes place in the plastic during molding (at an engineered temperature) which creates the cross-link structure. HDPE and XLPE have poor fuel permeation resistance characteristics while metal tanks do not permeate. There are several technological approaches that can be used to reduce gasoline permeation through plastic fuel tanks (HDPE and XLPE). These approaches include surface treatments, barrier constructions, and alternative materials.

Surface treatments, such as fluorination and sulfonation, could be used to meet the standard that EPA is considering. These treatments are performed as a secondary step after the fuel tank is molded; both create a thin layer on the inner or outer surfaces of the fuel tank that acts as a barrier to permeation. In fluorination, a barrier is created on both the inner and outer surfaces while in sulfonation, it is created only on the inner surface. These treatments do not materially change the construction of the fuel tank and are not expected to affect the durability of the fuel tanks because the barrier is not thicker than 20 microns thick and does not affect the tank wall material which is typically 3-6 mm thick. These approaches are both used to meet the current California gasoline permeation standards for portable fuel cans.

Multi-layer fuel tank constructions which create a barrier to permeation have been used in automotive applications for many years. The most common approach is to mold a thin layer of ethyl vinyl alcohol (EVOH) inside a HDPE shell. This approach is commonly used in high production volume, blow-molded fuel tanks but could be used in lower production volumes through a molding process known as thermoforming. Another approach available for blow-molded fuel tanks is to blend a small amount of EVOH directly into the HDPE. During molding, the EVOH creates non-continuous overlapping barrier platelets which restrict permeation. For each of these technologies, the barrier material is only a small percentage of the total makeup of the fuel tank. In addition, adhesion layers are used between the barrier and the HDPE shell to prevent the layers from pulling apart. These technologies have the advantage of having been in use for many years and having been demonstrated in automotive and other applications with no safety issues. Automotive manufacturers require the fuel tanks to meet wide range of durability tests on these fuel tanks including fuel exposure, flame tests, and low temperature drop impact tests.

Rotationally molded XLPE tanks would use one of several techniques to reduce permeation. In the first technique nylon, which has good permeability properties, is applied as an inner shell inside the fuel tank. The manufacturer has demonstrated that the nylon has an excellent bond with the XLPE.[1] As a result of this bond and the strength of the nylon, this construction offers strong resistance to impact. Testing at Imanna Laboratory, Inc. showed that a tank of this construction met the United States Coast Guard (USCG) durability requirements described in chapter 10 which include impact testing and flame resistance.[2] Another new approach for XLPE tanks is to coat the tank with a low permeation epoxy in a secondary step after molding. This approach does not change the basic fuel tank construction but only adds an outer layer similar in thickness as a coat of paint. A third approach for reducing permeation would be to rotomold the fuel tanks out of lower permeation materials such as nylons, acetal copolymers, or thermoplastic polyesters. Materials manufacturers have been working for years on engineered plastics that are compatible with the molding processes and design requirements of today's fuel tanks.

In the case where manufacturers make any changes to their fuel tanks, such as materials or geometry, they must evaluate the effect of these changes on their product. There are no standard procedures for evaluating the safety characteristics of these fuel tanks. Each vendor or manufacturer has developed their own tests to ensure performance. Examples of these durability tests include impact testing, temperature testing, and fuel exposure testing. It should be noted that EPA's permeation test procedures (contained in 40 CFR 1051.515) incorporate test requirements which will help to ensure the in-use integrity of these tanks. Current requirements include extended time of fuel soak in a 10 percent ethanol/gasoline blend, slosh testing, pressure-vacuum cycling, and prolonged exposure to ultraviolet light. Because there are not set industry standards for durability testing of fuel tanks, it may be helpful to consider additional tests which could address emissions durability such as high and low temperature cycling.

In none of these three approaches (surface treatment, barrier construction, and alternative materials) would EPA expect there to be an adverse incremental impact on safety. Surface treatments and barrier construction are used in portable and installed fuel tanks today. The choice of proper materials and construction durability is important and we believe that the manufacturer specific test procedures and production audits and EPA requirements are sufficient to ensure that there will be no increase in the types of fuel leaks that lead to fire and burn risk in use. There is also the potential for at least a directional improvement in safety in Phase 3 standards associated with reducing permeation of fuel vapor from the equipment in a closed space such as a shed or garage.

Running Loss

We are also considering several approaches to reducing the evaporative emissions associated with direct venting of fuel vapors from the fuel tank. We focus primarily on running loss venting emissions. When equipment is operating, the fuel is heated by the engine, the exhaust system, and possibly the hydraulic system. We are considering two primary approaches to controlling running loss venting emissions.

First, the equipment could be designed to minimize heat reaching the fuel tank. This could be achieved through heat shielding, changing from metal to plastic tanks, or by relocating the fuel tank further from heat sources. In the case of Class I equipment, the fuel tank could be moved away from the muffler to the opposite side of the engine block. On Class II equipment, there would be more room on the equipment to move the tank away from heat sources such as the engine or exhaust system. Overall, EPA expects this would be the preferred approach since it would be the least expensive way to comply with the test procedures and emissions standards under consideration. If the fuel tank is moved away from heat sources, the likelihood of fuel spilling on a hot surface during refueling would also be reduced. Heat shielding and changing tank material would also reduce heat getting to the fuel. Changing from metal to plastic tanks where practical would also substantially reduce running loss emissions and the overall hot surface area.

The second approach to controlling running loss emissions would be to route the vapor to the engine intake to be burned by the engine. A restriction would need to be placed in the vent line to the engine to keep the engine manifold vacuum from drawing too much vapor from the fuel tank. This restriction could be in the form of a limited flow orifice or a valve. This would have the additional benefit of acting as a rollover valve since the limiting orifice or valve restricting vapor flow would inhibit fuel flow from the tank if the equipment was inverted. Even without moving the fuel tank, the equipment could be designed to prevent fuel spillage during refueling from reaching hot surfaces that could ignite the fuel. As discussed above, some manufacturers design their equipment to prevent fuel overfill from reaching these hot surfaces consistent with ANSI B71.1, B71.3, and B71.4.

To control diffusion-related venting emissions, manufacturers could make use of fuel caps with no venting or with venting through a tortuous path. These caps, which are used in some applications today, would reduce fuel spillage when the equipment is turned over or even due to sloshing in the fuel tank. The chance of a fuel cap being lost could be reduced with a tether which could reduce the chance of fuel spillage due to open or improperly plugged fill necks. We would expect to accomplish this type of control as part of our running loss control requirements.

Conclusion

NHH equipment is capable of achieving reductions in fuel tank permeation, fuel hose permeation, and fuel tank vapor venting emissions without an adverse incremental impact on safety.

For fuel hoses and fuel tanks the applicable consensus standards, manufacturer specific test procedures and EPA requirements are sufficient to ensure that there will be no increase in the types of fuel leaks that lead to fire and burn risk in use. The running loss control program being considered by EPA will create requirements that will reduce risk of fire in use. Moving fuel tanks away from heat sources, improving cap designs to limit leakage on tip over, and requiring a tethered cap will all help to eliminate conditions which lead to in-use problems related to fuel leaks and spillage.

Furthermore, reductions in permeation emissions and the techniques for reducing running loss emissions are likely to have a salutary impact on the overall safety of NHH systems. The evaporative emission standards under consideration would lead to significant reductions in fuel vapor emitted to the atmosphere. This is especially important in closed spaces because evaporative emissions occur regardless of whether the equipment is operated (i.e. a piece of equipment stored in a shed with fuel in the tank continues to permeate and vent fuel vapor into the shed); such controls could prevent vapor concentrations in closed spaces from becoming high enough for the vapor to reach a flammable mixture. Exposing the fuel tank to less heat may also reduce post shutdown hot soak emissions from the tank.

HH Equipment

We are considering fuel hose and fuel tank permeation emission standards for HH equipment. The standards and test procedures would be similar to those discussed above for NHH engines.

Fuel Hose

For the most part there are no significant differences in the fuel hose related safety issues for NHH and HH engines and equipment. Although somewhat different constructions are used today, manufacturers perform many durability tests on HH hose as well. These tests are described above. HH equipment manufacturers can make use of the same low permeation hose materials and constructions described above for NHH equipment. These low permeation hose constructions use a fluoroelastomer or fluoroplastic material as a barrier. Alternatively, the entire fuel hose could be molded from a fluoroelastomer.

In some applications, molded fuel hoses are used rather than simple extruded fuel hose. These fuel hoses are typically either molded out of nitrile rubber or a fluoroelastomer. Fluoroelastomers are essentially rubber impregnated with fluorine which results in good fuel permeation resistance. Manufacturers of equipment that may be used in cold weather have stated that they must use nitrile rubber because the fluorelastomer material may become brittle at very low temperatures. While they have presented data supporting this claim, it was based on a fluoroelastomer without a low temperature additive package. Fluoroelastomers used in automotive applications use low temperature additive packages and are designed for strength at temperatures as low as -40°C. In addition, at least one snowmobile manufacturer has recently begun using a low temperature fluoroelastomer for its fuel system seals. Fuel hose meeting SAE and ASTM standards is available today which meets a widespread set of safety and durability requirements.

Manufacturers have claimed that barrier hoses are stiffer and may not hold on to hose connections as well as nitrile rubber hose. The barriers used in low permeation hose are thin and, in our evaluation, barrier hose is not noticeably different in stiffness than nitrile hose and fits well over typical hose barbs used today. If a manufacturer felt it was necessary, there is a wide range of fuel hose clamps available today.

Manufacturers have indicated that they would perform durability testing on any new hose constructions they were to use. These tests are described above. In addition, manufacturers have stated that they would test the low permeation hose on their equipment under field testing. Based on these practices and the properties of the low permeation materials discussed above, the low permeation fuel hose requirements being considered by EPA would not lead to an increase in fuel leaks or risk of fire or burn in use.

Fuel Tanks

Most fuel tanks on HH equipment are made of HDPE. EPA expects emission reductions would be achieved through the surface treatments or barrier technologies identified for NHH equipment and that the in-use safety experience would be similar. The surface treatments described above were fluorination and sulfonation. The barrier treatments described above included a thin EVOH barrier layer within a HDPE shell and non-continuous barrier platelets created by blending the EVOH into the HDPE prior to molding. As discussed above, the surface treatments do not change the construction of the fuel tank but only put a microscopic barrier on the outer surface. The barrier technologies only make up a small fraction of the total material of the fuel tank and have been long demonstrated in automotive and other applications.

Manufacturers of equipment with structurally integrated fuel tanks have stated that they must use nylon because of its structural qualities. An additional advantage of nylon is that it has lower permeation rates than HDPE. However, on test fuel containing ethanol, the permeation rate through nylon fuel tanks is still slightly higher than the permeation standard under consideration. Under the program we are considering, EPA expects that manufacturers using nylon in their structurally integrated tanks will be able to continue to do so. Thus, EPA expects there will be no change and thus no increase in risk.

Conclusion

HH equipment is capable of achieving reductions in fuel tank permeation and fuel hose permeation without an adverse incremental impact on safety. For fuel hoses and fuel tanks the applicable consensus standards, manufacturer specific test procedures and EPA requirements are sufficient to ensure that there will be no increase in the types of fuel leaks that lead to fire and burn risk in use. The evaporative emission standards under consideration would lead to significant reductions in fuel vapor emitted to the atmosphere. This is especially important in closed spaces because evaporative emissions occur regardless of whether the equipment is operated; such controls could prevent vapor concentrations in closed spaces from becoming high enough for the vapor to reach a flammable mixture.

E. CONCLUSION

EPA has reviewed the fuel hose and fuel tank characteristics for NHH and HH equipment and evaluated control technology which could be used to reduce evaporative emissions from these two subcategories. This equipment is capable of achieving reductions in fuel tank and fuel hose permeation without an adverse incremental impact on safety. For fuel hoses and fuel tanks, the applicable consensus standards, manufacturer specific test procedures and EPA requirements are sufficient to ensure that there will be no increase in the types of fuel leaks that lead to fire and burn risk in use. Instead, these standards will reduce vapor emissions both during operation and in storage. That reduction, coupled with some expected equipment redesign, is expected to lead to reductions in the risk of fire or burn without affecting component durability. Additionally, the running loss control program being considered by EPA for NHH equipment will lead to changes that are expected to reduce risk of fire in use. Moving fuel tanks away from heat sources, improving cap designs to limit leakage on tip over, and requiring a tethered cap will all help to eliminate conditions which lead to in-use problems related to fuel leaks and spillage. Therefore, EPA believes that the application of emission control technology to reduce evaporative emissions from these two subcategories will not lead to an increase in incremental risk of fires or burns and in some cases is likely to at least directionally reduce such risks.

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[1] O'Brien, G., Partridge, R., Clay, B., "New Materials and Multi-Layer Rotomolding Technology for Higher Barrier Performance Rotomolded Tanks," Atofina Chemicals, 2004, Docket EPA-HQ-OAR-2004-0008-0044.

[2] Partridge, R., "Petro-Seal for Ultra-low Fuel Permeation; Evaporative EPA Emissions from Boat Fuel Systems," Arkema, Presentation at the 2004 International Boatbuilders' Exhibition and Conference, October 25, 2004, Docket EPA-HQ-OAR-2004-0008-0252.

10. Safety Analysis for Marine SI

This section gives an overview of Marine SI engines and vessels that may be impacted by further exhaust and evaporative emission control requirements. It also provides the technical basis and analysis for our assessment of the incremental impact on safety of potential marine SI exhaust and fuel evaporative emission standards

A. CURRENT TECHNOLOGY

Marine Engines

Marine SI engines are typically grouped into the following categories:

1. Outboards (OB). These are engines mounted on the stern of a boat with the entire engine and drive assembly external to the hull. Outboards range in power from less than 2 horsepower (hp) to more than 250 hp. More than half of the outboards sold in the US are less than 50 hp.

2. Personal watercraft (PWC). These vessels are generally intended for 1-3 riders where the riders sit (or stand) on top of the vessel with their legs straddling it. Examples of PWC include Jet skis, Wave runners and Sea Doo watercraft. Traditional PWC sold today are all above 50 hp, but some lower power specialty applications, such as motorized surfboards, fall into this category as well.

3. Sterndrives and Inboards (SD/I). These engines are typically built by adding marine components to automotive engine blocks and range in power from about 130 hp to more than 1000 hp. A stern drive engine (also known as an inboard/outboard) is mounted in the stern of the boat and has a direct drive through the hull similar to an outboard drive. An inboard engine is generally mounted in the center or rear of the vessel and the engine is linked to the propeller by a drive shaft.

4. Marine auxiliary engines. These are small engines used on boats for auxiliary power. Although they are currently categorized as Class I NHH engines (and in some cases Class II NHH engines), they have features that are unique to marine applications. Specifically, they make use of their environment to water-cool the engine and water-jacket the exhaust.

This study focuses on engines less than 50 hp. For this reason we only include OB, PWC, and marine generator sets in the following discussion.

To meet existing emission standards, OB and PWC manufacturers are converting much of their product mix from traditional crankcase scavenged carbureted two-stroke engines to either four-stroke engines or two-stroke direct injection engines. Smaller four-stroke engines (<25 hp) are anticipated to continue to use carburetion; however, electronic fuel injection is becoming popular on larger engines.

PWCs have a fuel tank integrated into the vessel/engine structure and all is sold as a unit. OB engines are self contained power units but typically do not have an attached fuel tank. Either a portable fuel tank is used with the engine (mostly for smaller engines) or the engine is connected to a fuel tank in the vessel that is permanently installed by the boat builder.

As stated above, engines used in marine generator sets are water cooled with water-jacketed exhaust. The purpose of the water-jacketing is to maintain low surface temperatures to minimize exhaust system temperatures. These engines are often packaged in small compartments on boats and could overheat if they relied solely on ambient air for the cooling system. Two engine manufacturers currently dominate this niche market. Recently, both manufacturers have introduced models with electronic fuel injection and catalysts in the exhaust system and have stated their intentions to convert to catalyzed engines in the near future. Catalyst technology has been driven by the desire to reduce carbon monoxide emissions. Known carbon monoxide poisonings have been disproportionately high among boats with generators compared to other vessels.

Marine Vessel Fuel Systems

The marine vessels under consideration here include those powered by OB and PWC engines. The marine industry has both mandatory and voluntary standards for boat construction (discussed below) which include requirements for fuel system components such as fuel hoses and fuel tanks.

Vessels powered with OB engines use both portable and installed tanks. Portable marine fuel tanks, which are used primarily with small OB engines, are normally 5-6 gallons. They are normally designed of blow-molded HDPE. They are designed with a quick connect fitting for the fuel hose which closes and seals the system when not in use. Outboard vessels with installed fuel tanks primarily use roto-molded XLPE fuel tanks. However, fuel tanks made of aluminum or fiberglass are also used, primarily on larger vessels. These tanks range in capacity from 12 gallons to well over 100 gallons. Outboard vessels with installed tanks generally follow the recommended industry practice of venting the fuel tank though a hose which extends to the outside of the hull. Thus diurnal emissions are uncontrolled.

Fuel tanks used on PWC are installed by the vessel manufacturer. They range in size from 4-18 gallons and are usually constructed of blow-molded HDPE. Fuel tanks on PWC are sealed with pressure relief valves so there are low diurnal emissions. The purpose of sealing the fuel tank is to prevent fuel spillage into the water during use.

Fuel hoses include those carrying liquid fuel as well as those carrying fuel vapor. OB engines employ fuel hoses on the engine and come with a fuel hose to be connected to the portable or the installed fuel tank. For those OB engines with installed fuel tanks, there is a fuel fill hose through which gasoline enters the fuel tank and another smaller diameter hose used to vent the fuel tank. Fuel hose is generally constructed of polyvinyl chloride or nitrile rubber with an abrasion-resistant cover and often a braid or wire reinforcement. The fuel, vent, and fill neck hoses can range from only a few feet in length to dozens of feet in length depending on the size of the vessel, the location of the fuel tank and engine, and the location of the tank vents and fill caps. For portable fuel tanks, the hose is generally about 6 feet in length and includes quick connections at both ends and a rubber primer bulb in the middle. Portable fuel tanks vent through a fuel cap mounted directly on the fuel tank so there is no vent hose.

PWC come with a fully installed fuel system. The fuel hoses include those used to route fuel to the engine as well as those used to draw fuel from the installed fuel tank. These tanks are normally top fill so there is no appreciable fuel fill neck involved.

B. IN-USE SAFETY EXPERIENCE

As discussed in earlier chapters, assessing incremental risk requires an understanding of the problems and in-use safety experience with current products. For this analysis we used data available on the USCG website for marine vessels. Presented below are incidences that are relevant to the engine/equipment subsystems that may be affected by our emission standards.

Marine Engines and Vessels

The USCG website (www.uscgboating.org) includes boating statistics developed from the recreational boat numbering and casualty reporting systems. The most recent publication on these statistics is “Boating Statistics – 2004” which includes a five year summary of boating accidents. The table 10-1 presents boating accidents related to fuel fires.

Table 10-1: Coast Guard Five Year Summary of Fuel Related Fires

Type of Accident	Year	Incidences	Fatalities	Injuries
Fire or Explosion of Fuel	2004	162	4	158
	2003	142	7	68
	2002	160	4	82
	2001	153	2	73
	2000	183	2	93

The above statistics only include incidences that are reported to USCG under 33 CFR 173.55. Because this regulation places minimum thresholds on property damage or treatment requirements, incidences may go unreported. Additionally, the USCG report does not provide any more detail on the causes of the fuel related fires. Even looking into the incidence reports, details are not generally given on the source of the fuel or fuel vapor leading to the fire or explosion. In many of the incidence reports the operator stated that they had just started their engine when the fire started. Recommended practice is to run a blower to remove fuel vapor from the engine compartment prior to starting the engine. The purpose of this is to remove fuel vapor that could be a fire hazard. This fuel vapor may come from fuel spillage, leaks in the fuel system, and/or permeation through plastic tanks and rubber hoses.

C. CURRENT SAFETY STANDARDS

The marine industry is regulated for safety primarily by USCG. In addition, USCG standards are supplemented by voluntary standards created by the American Boat and Yacht Council (ABYC) Reference is also made to SAE and Underwriters Laboratories tests and standards. These standards cover a wide range of boating safety issues which include engine installations and fuel system requirements. All of the technologies being considered for controlling exhaust and evaporative emissions from marine engines are covered by these safety requirements. These include:

33 CFR 183 Subparts J and K
ABYC H-2, H-24, H-25, P-1, and TH-23
UL 1102 and 1185
SAE J1527 and J2046

Marine Engines

The primary safety issues related to exhaust emission controls pertain to maximum exhaust system surface temperatures, the risk of exhaust system leaks (i.e. carbon monoxide) into the vessel, and the risk of flammable gasoline vapor mixtures around an engine. As discussed above, marine engines used in recreational vessels typically have water-jacketed exhaust to minimize the temperature of exposed surfaces.

USCG safety requirements for boats and associated equipment are contained in 33 CFR 183. Subpart J deals specifically with fuel systems on boats and includes specifications for fuel pumps and carburetors on the engine. The scope of Subpart J includes all gasoline propulsion and auxiliary marine engines, excluding outboards. These regulations state that the fuel pump must be on the engine or within 12 inches of the engine and that it must not leak fuel even if the diaphragm fails. These regulations also limit the amount that a carburetor may leak under several specified conditions and require anti-siphon valves and fuel shut off valves under specific conditions. The purpose of these requirements is to minimize the risk of fuel spilling into the boat. In addition 46 CFR part 58 includes installation requirements for gasoline marine engines. These installation requirements include backfire flame control, drip collectors for carburetors, cooling or insulation for the exhaust system, and safe exhaust pipe installations. These regulations do not apply to OB engines because they are not considered to be permanently installed. Supplemental recommended practice for electric fuel transfer pumps is included in ABYC H-24 which specifies delivery hose length, outlet pressure, and when the pump may be energized.

The only USCG safety standards that directly apply to OB engines are in 33 CFR 183, Subpart L. These standards require that outboards capable of a minimum specified thrust must be equipped with a device to prevent the OB from being started in gear. USCG has not promulgated further safety standards for OB engines primarily because the need has not been demonstrated for further regulation.

USCG standards for ventilation of vapors from boats with gasoline engines (auxiliary or propulsion) are contained in 33 CFR 183, Subpart K. Subpart K requires that each compartment containing a gasoline engine be open to the atmosphere or be vented by a blower system. Where a powered ventilation system is required, USCG requires a label stating “Warning—gasoline vapors can explode. Before starting engine, operate blower for 4 minutes and check engine compartment bilge for gasoline vapors.” These ventilation requirements are supplemented by ABYC H-2 which also requires compartments with non-metallic fuel tanks to be vented to atmosphere.

ABYC P-1 states that all surfaces on the exhaust system on permanently installed marine engines that may come into contact with persons or gear must be at or below 200°F or have protective guards, jacketing, or covers.

ABYC also details recommended practices for minimizing the risk of CO exposure on boats. These recommended practices are described in ABYC TH-23 which is a technical report intended for design, construction, and testing criteria to identify and minimize the presence of CO around a boat with a gasoline propulsion or auxiliary marine engine.

Marine Vessel Fuel Systems

The primary safety issue regarding marine fuel systems is to prevent fuel from leaking into the boat. USCG requirements for marine fuel systems are located in 33 CFR 183, Subpart J. Subpart J deals specifically with fuel systems on boats and contains durability and other design requirements for fuel tanks and fuel hoses. It should be noted that Subpart J applies to all boats that have gasoline engines (propulsion and/or auxiliary), except for OB engines. However, ABYC H-24 supplements 33 CFR 183 and extends these practices to all boats with gasoline fuel systems, including OB engines. Some smaller boats do not have installed gasoline fuel systems. Operators of these boats use OB engines attached to portable fuel tanks which are covered by ABYC H-25. Specifications for marine fuel hoses and fuel tanks are discussed below.

Fuel Hoses

Both 33 CFR 183 and ABYC H-24 reference SAE J1527 for the proper design of marine fuel hoses. The USCG regulations and SAE recommended practice distinguishes between Type A and Type B fuel hose. Type A fuel hose normally contains liquid fuel while Type B hose normally contains no liquid fuel. Both hose types are subject to the 2½ minute flame test under 33 CFR 183, Subpart J; however, Type B hose has a more relaxed permeation requirement.. In addition, both types of hose must still be self extinguishing within 60 seconds when burned. SAE J 1527 includes several other durability tests including abrasion resistance, burst pressure, vacuum collapse, cold temperature flexibility, tensile strength and elongation, oil resistance, ozone resistance, and fuel resistance tests on ASTM fuel C and a test fuel containing 85 percent ASTM fuel C and 15 percent methanol. The fuel resistance tests state that the hose must meet maximum tensile change, elongation change, and volume changes after being immersed in the test fuels. Also, SAE J1527 specifies maximum allowable permeation rates on the two test fuels. Finally, this recommended practice includes an adhesion test which sets a minimum load required to separate the tube from the protective cover.

PWC manufacturers generally use an alternative recommended practice provided under SAE J2046 for their fuel system designs. This recommended practice includes tests and limits for tensile strength and elongation, dry heat resistance, ozone resistance, oil heat resistance, burst pressure, vacuum collapse, cold temperature flexibility, and resistance to ASTM fuel C. This fuel resistance includes immersing the hose in fuel and testing the tensile change, elongation change, and volume change. Also, a permeation limit is set for ASTM fuel C. In addition, SAE J2046 contains an adhesion test which sets a minimum load for separating the tube and cover. Finally, this recommended practice includes a 2½ minute flame test for the entire fuel system.

For fuel hose used with portable fuel tanks, UL 1185 recommends that fuel hose meet the USCG Type A or Type B standards discussed above.

Fuel Tanks

33 CFR 183 Subpart J includes several specifications and durability tests for marine fuel tanks which are installed in vessels with gasoline propulsion or auxiliary engines, excluding OB engines. These fuel tank specifications include prohibited materials, labeling requirements, and a limit on the pressure in the fuel tank of 80 percent of the pressure marked on the label that the tank can withstand without leaking (at least 3 psi). The fuel tanks must pass several durability tests without leaking. These durability tests include a static pressure test, a shock test, a pressure impulse test (25,000 cycles from 0-3 psi), a slosh test (500,000 cycles ± 15° from level), and a 2½ minute fire test.

ABYC H-24 supplements 33 CFR 183 and extends these practices to all gasoline powered boats with installed fuel tanks, including those using OB engines. One notable addition is that ABYC H-24 requires a 5/8" ID vent hose to prevent pressure from building up in the fuel tank. Additional requirements are contained in UL 1102 which references ASTM H-24 and 33 CFR 183, Subpart J. These additional requirements include shock testing of fittings, a static pressure test, and requirements for gaskets to be tested for fuel and oil resistance and atmospheric aging.

ABYC H-25 defines recommended practices for the design of portable marine fuel tanks. These specifications include requirements for color (red), UV inhibitors, mechanical strength from -18°C to 60°C, labeling, and vent openings that can be closed so that they are liquid and vapor tight. This recommended practice includes several durability tests as well. These durability tests include a low temperature drop test, exposure to a test fuel of 85 percent ASTM fuel C blended with 15 percent methanol, and an expansion and contraction test. UL 1185 includes additional requirements including standards for fittings and accessories integral to the portable fuel tank such as the fuel hose and the quick connect fittings. Additional tests for the fuel tank include vibration, durability of vent and fill closures, fitting impact, permeation, light and water exposure, and a fire test. In addition there are requirements for gaskets to be tested for fuel and oil resistance and atmospheric aging.

D. EMISSION CONTROL SYSTEM DESIGN

Marine Engines

We expect to propose emission standards for OB and PWC that will require significant upgrades in fuel systems and calibration. These standards are expected to eliminate carbureted two-stroke engines from the market. These 2-stroke engines have short-circuiting losses in the cylinder due to the intake and exhaust valves being open at the same time. As a result, 25 percent or more of the fuel passes through the engine unburned. Over the past decade, manufacturers have introduced lower emitting four-stroke or direct-injection two-stroke engines across their entire product lines. We anticipate that further emission controls will result in manufacturers discontinuing their older carbureted two-stroke engine lines and selling only their cleaner four-stroke or direct-injection two-stroke designs. We do not expect that the potential exhaust emission standards would require after-treatment technology for control of exhaust emissions. We are not anticipating the use of new technology to meet the exhaust emissions standards but only the expanded use of current cleaner technologies.

Marine Auxiliary Engines

These are small engines used on boats for auxiliary power, in most cases for electric power generation. Although they are currently categorized as Class I NHH engines (and in some cases Class II NHH engines), they have features that are unique to marine applications. Specifically, they make use of their environment to water-cool the engine and water-jacket the exhaust. Marine auxiliary engine manufacturers have aggressively pursued the development of advanced emission control technology for these products in response to market place concerns. These systems use catalytic converters inside of a water-jacketed system and electronic feedback controls to give optimum air to fuel ratio. This emission control approach allows for very low exhaust emission levels relative to current NHH HC+NOx and CO emission standards.

Marine Vessels

We have already proposed evaporative emission standards for vessels powered by Marine SI engines that are similar in scope to those discussed above for nonhandheld land-based engines. These include fuel hose and fuel tank permeation control. Also, while we are not proposing standards for controlling vessel running loss emissions, we have already proposed standards requiring the control of diurnal emissions.

Fuel Hose

Most marine vessels using SI engines use polyvinyl chloride or nitrile rubber hose to deliver gasoline from the fuel tank to the engine. To meet the fuel hose permeation standards under consideration, manufacturers would be able to use the current basic type of hose construction except that an additional barrier layer would need to be added to the construction. A typical barrier material would likely be a fluoroelastomer or fluoroplastic material. Current fuel lines used in marine applications meet USCG and ABYC standards for flame resistance and durability as well as requirements for fuel system fittings and clamps. The barrier layers needed to control permeation are thin and are not expected to lead to any significant differences in hose flexibility or ability to retain connections within the fuel system. The hose which could be used is commercially available today.

Fuel tanks

Marine fuel tanks include portable tanks constructed of HDPE and installed fuel tanks made of XLPE, aluminum, and fiberglass. Portable fuel tanks made of HDPE are used in PWCs and with lower horsepower OB engines. Aluminum, fiberglass, and XLPE are used in installed tanks in vessels using higher horsepower OB engines. HDPE, XLPE, and fiberglass have poor permeation resistance characteristics. Fuel does not permeate through aluminum tanks. As was the case with NHH engines and equipment, there are several technological approaches that can be used to reduce gasoline permeation through plastic fuel tanks. These approaches include surface treatments, barrier constructions, and alternative materials.

Surface treatments, such as fluorination and sulfonation, do not materially change the construction of the fuel tank. These treatments are performed as a secondary step after the fuel tank is molded and create a thin layer on the surfaces of the fuel tank that acts as a barrier to permeation. In fluorination a barrier is created on both the inner and outer surfaces while in sulfonation it is created only on the inner surface. These treatments do not materially change the construction of the fuel tank and are not expected to affect the durability of the fuel tank because the barrier is less than 20 microns thick. Surface treatments are used to meet the California gasoline permeation standards for portable fuel cans.

Multi-layer fuel tank constructions which create a barrier to permeation have been used in automotive applications for many years. The most common approach is to mold a thin layer of ethyl vinyl alcohol (EVOH) inside a HDPE shell. This approach is commonly used in high production volume, blow-molded fuel tanks and can be used in lower production volumes through a molding process known as thermoforming. Another approach available for blow-molded fuel tanks is to create a non-continuous barrier by blending a small amount of EVOH directly into the HDPE. During molding, the EVOH creates overlapping barrier platelets which restrict permeation. For each of these technologies, the barrier material is only a small percentage of the total makeup of the fuel tank. Non-continuous barriers can reduce permeation by more than 85 percent while continuous barriers can achieve more than a 99 percent reduction in permeation. These technologies have the advantage of having been in use for many years and having been applied in various applications. Automotive manufacturers require these fuel tanks to meet durability specifications similar to those required by the US Coast Guard.

Rotationally molded XLPE tanks would be able to make use of barrier technologies. In one technique nylon, which has good permeability properties, is applied as an inner shell inside the fuel tank. The manufacturer has demonstrated that the nylon has an excellent bond with the XLPE.[1] As a result of this bond and the strength of the nylon, this construction offers strong resistance to impact. Testing at IMANNA labs showed that a tank of this construction met the USCG durability requirements in 33 CFR 183, Subpart J which includes impact testing and flame resistance.[2] As a result of this bond and the strength of the nylon, the construction meets the USCG impact and flame resistance requirements discussed above. In addition, emission testing has shown good permeation control performance compared to baseline. Another new approach for XLPE tanks is to coat the tank with a low permeation epoxy in a secondary step after molding.[3] This approach does not change the basic fuel tank construction but only adds an outer layer similar in thickness as a coat of paint. In addition, an intumescent additive has been developed which can be added to the epoxy coating for additional flame resistance. Emission testing on this technology has also shown good emission control performance.

Fiberglass fuel tanks can meet low permeation requirements through the use of a nanocomposite barrier layer. This barrier layer is composed of fiberglass impregnated with microscopic fibers of treated volcanic ash. A company named ECSI has developed this technology for use in marine fuel tanks. Through testing, ECSI has demonstrated this technology to meet USCG and ABYC standards for fuel system mechanical strength requirements.[4] In addition, emission testing has shown good emission control performance.

Diurnal Emissions Control

As was discussed in the beginning of Chapter 9, diurnal emissions occur when the rising ambient temperature heats the fuel inside the fuel tank and displaces the fuel vapors created through fuel tank vents. In the cases where these venting emissions are high, a combustible fuel vapor concentration could occur if the vapor is vented into an enclosed space such as the confines a vessel. In addition, fuel vapor vents create a path for fuel to spill out of the fuel system during refueling or when fuel sloshing occurs.

The simplest approach to controlling diurnal emissions is simply to close the tank vent. Under this scenario, when the tank heats up, pressure would build in the fuel tank, but no fuel vapor would be vented to the atmosphere. Pressure would be limited with a pressure relief valve that would open at higher pressures. In addition, a vacuum relief valve would be needed to prevent a vacuum in the fuel tank which could restrict fuel delivery to the engine and cause the engine to stall. This is really only an option for smaller tanks where the potential for significant geometric shape deformation under pressure is small. Portable marine fuel tanks are designed to be sealed when not in use, and PWC use sealed fuel tanks (with pressure relief valves) to prevent spillage during operation. Leakage from these tanks is normally not into a confined space such as a vessel bilge.

Another well developed approach to controlling diurnal emissions has been used in automobiles for over 30 years. In this approach a plastic canister containing activated carbon is placed in the vent line. This carbon canister collects fuel vapor vented from the fuel tank as it breathes during the day. The canister could then be either actively or passively purged. Active purging refers to drawing the vapor to the engine to be burned. Passive purging refers to removing gasoline vapor stored on the activated carbon through the air naturally drawn into the fuel tank through the vent line during cooling periods. Canister systems represent a simple technology that has long been demonstrated in various applications without safety issues.[5]

E. ASSESSMENT OF SAFETY IMPACT OF NEW EMISSION STANDARDS

New Exhaust Emission Standards for OB/PWC

Because we are not anticipating the use of new technology to meet the exhaust emissions standards, we do not believe that further emission control will result in an incremental safety risks relative to the current mix of technology. Current 4-stroke and 2-strke direct injection technologies are more sophisticated than the older carbureted two-stroke design and have been used for nearly a decade. Although there were some early technical issues with two-stroke direct injection engines, these issues have been largely resolved though significant engineering efforts. As a result of these engineering efforts, the newer 4-stroke and 2-stroke direct injection technologies are actually more reliable than older designs. In addition, they are more fuel efficient which allows for greater range and, arguably a lower chance of running out of fuel. These improvements in reliability and range would be expected to improve safety issues related to being stranded at sea.

New Exhaust Emission Standards for Marine Auxiliary Generators

Manufacturers of marine auxiliary engines are leading the way in new exhaust emission control technology in the marine sector. Even with catalysts packaged in the exhaust manifold, these engines have low surface temperatures because the exhaust manifolds containing the catalysts are water-jacketed with surface water drawn and returned to the ambient source to cool the exhaust system. With water jacket cooling EPA does not anticipate any heat-related problems or increase in fire due to catalysts. In addition, these systems are electronically controlled with feedback systems that can be used to detect problems with the engine before they become problematic. Finally, a safety benefit is achieved by the very large reduction in CO emissions from these engines. This reduction in CO will benefit not only the boat operators but swimmers and other individuals in the vicinity of the boat.

Fuel Hose Permeation Standards

Low permeation fuel hose subject to the USCG requirements would still need to meet the requirements specified in SAE J1527 and discussed above. In fact, one manufacturer is selling barrier fuel hose today that meets the USCG requirements and is used by several boat builders. This hose meets the permeation requirements we are considering. This hose construction is similar to baseline hose constructions except that a barrier layer is added. In the same way, manufacturers of PWC and portable fuel tanks, would still be expected to comply with SAE J2046 and UL 1185 respectively. To meet the fuel hose permeation standards under consideration, manufacturers would be able to use the existing hose constructions except that an additional barrier layer would need to be added to minimize permeation fuel through the hose material.

Low permeation fuel hose will have no negative implications for safety and may have some benefits. The addition of a barrier layer would not require a change in the general construction of the hose. In addition, barrier materials are made of compounds that are resistant to permeation by gasoline, including ethanol blends and oxidized ("sour") gasoline. This fuel resistance not only protects against chemical attack, but also limits swelling due to the permeation of fuel. By limiting the swelling and contracting (drying) cycles and chemical attacks that may cause the hose to eventually become brittle, the hose may better resist cracking as well. The barrier hose may reduce concentrations of fuel vapor in confined spaces where the fuel hoses are routed such as the engine compartment, vessel bilge, or other areas in the hull where the fuel tank may be located.

This lower concentration could help prevent a flammable mixture of fuel vapor from forming within the confines of the vessel. It should be noted that low permeation fuel hose is available today and is used by many boat builders.

Fuel system fittings and clamps are also covered by the USCG and ABYC standards. These specifications require the fittings to have a bead, flare, or other grooves to help prevent the hose from pulling off the fittings. Clamps must be corrosion resistant, not cut the hose, and resist one pound tensile force. In addition, all fittings, joints, and connections must be easily accessible for inspection and maintenance. With any changes in hose constructions, boat builders would still need to design their connections to meet these requirements. As some boat builders are using low permeation fuel hose today, they are also using corresponding fittings and clamps.

Fuel Tank Permeation Standards

In any situation where a manufacturer makes changes to fuel tanks, such as materials or geometry, they must evaluate the potential safety effects of these changes. Under current industry practices new fuel tank designs are durability tested under the USCG requirements and ABYC and UL recommended practice described above. These tests include pressure impulse, fuel and oil exposure, atmospheric aging, slosh, shock, and flame resistance.

The techniques suggested above would also meet the USCG and ABYC durability requirements including the flame test

We expect that the use of low permeation fuel tanks will have no negative implications for safety and may have some benefits. Permeation barriers could minimize permeation of the fuel into the tank walls and reduce any negative effects of fuel exposure. In addition, low permeation fuel tanks would lead to reduced concentrations of fuel vapor in confined spaces in the vessel hull where the fuel tank is located; a lower fuel vapor concentration means a reduced risk of fire. The choice of proper materials and construction durability is also important.

Under our current permeation requirements for recreational vehicles, we require durability testing as part of the fuel tank permeation test procedure. Prior to the permeation test, the fuel tank is filled with gasoline containing 10% ethanol and soaked for 20 weeks at 28±5°C. In addition, the fuel tank is subject to a pressure vacuum test made up of 10,000 cycles from -0.5 to 2.0 psi, a slosh test made up 1 million cycles where the tank is rocked ±°15, and a 240 hour UV exposure test. Although these tests are intended to help ensure the long term effectiveness of the permeation control technology, they also inherently assess the durability of the fuel tank as well.

Fuel Tank Diurnal Emission Control Standards

Portable fuel tanks are currently designed to be pressurized through a manual control valve on the vent. The use of a sealed tank with vacuum relief would not add to the pressure experienced by the fuel tank and therefore offer no incremental safety risk. The vacuum relief valve could offer a safety benefit in that it could prevent occurrences of engine stalling that may occur if the operator were to forget to open the manual valve prior to starting the engine. PWC fuel tanks are already using sealed fuel systems with pressure relief valves. We expect that this design would meet the emission control requirements under consideration.

Carbon canisters do not present an incremental risk to safety for marine vessel use. These canisters are passive systems in the vent line and create nothing more than nominal backpressure on the tank. The use of the carbon canister can have positive safety implications. First, the carbon will collect vapor from the fuel tank which will result in less gasoline vapor which can infiltrate the engine and bilge areas on the boat. Second, the design of the diurnal control system will include a mechanism to prevent fuel from entering the vent hose during refueling. This mechanism could be as simple as a small orifice between the fuel tank and the canister that would be sized to limit fuel from entering the vent hose during refueling but be large enough to prevent a restriction on vapor flow during diurnal breathing. For an average fuel tank, this orifice would be on the order of 1mm in diameter. This could help reduce fuel spillage that sometimes occurs today from the vent line during refueling. Because the fuel tank would need to vent through the canister to achieve the emission reductions, the fuel cap would need to form a vapor tight seal. Four boat manufacturers installed carbon canisters last summer on a total of fourteen boats as part of a demonstration project. At the end of the summer, all of the canisters were still operating properly and no safety incidences were reported.[6]

F. CONCLUSION

EPA reviewed the characteristics of marine engines less than 50 horsepower and evaluated the emission control technologies used to reduce exhaust emissions from these engines. EPA also reviewed the fuel system characteristics for marine vessels using these engines and evaluated emission control technologies which could be used to reduce fuel evaporative emissions from these two subcategories. Marine engines including marine auxiliary engines must meet USCG standards related to safety. In addition, it is industry practice to meet ABYC requirements. There are thousands of 4-stroke and 2-stroke direct injection engines in the fleet today which would meet the exhaust emission standards being considered by EPA. Based on the fact that the technology needed to meet the standards we are considering is already in use in both OB and PWC engines, EPA does not believe that the technology needed to meet new standards would result in an increase of risk of fire and burn to consumers in use.

With regard to fuel hoses, fuel tanks, and diurnal controls, there are rigorous USCG, ABYC, UL, and SAE standards which manufacturers will continue to meet for fuel system components. In addition, USCG and others would be able to expand their requirements in response to new fuel systems designs if they saw the need to do so. Furthermore, the EPA permeation certification requirements related to emissions durability will add an additional layer of assurance. Low permeation fuel hoses are used safely today in many marine vessels. Low permeation fuel tanks and diurnal emission controls have been demonstrated in various applications for many years without an increase in safety risk.

Furthermore, a properly designed fuel system with fuel tank and fuel hose permeation controls and diurnal emission controls would reduce the fuel vapor in the boat, thereby reducing the opportunities for fuel related fires. In addition, using improved low permeation materials coupled with designs meeting USCG and ABYC requirements should reduce the risk of fuel leaks into the vessel. EPA believes that the application of emission control technologies on marine engines and vessels for meeting the proposed evaporative emissions standards would not lead to an increase in incremental risk of fires or burns.

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[1] O'Brien, G., Partridge, R., Clay, B., "New Materials and Multi-Layer Rotomolding Technology for Higher Barrier Performance Rotomolded Tanks," Atofina Chemicals, 2004, Docket EPA-HQ-OAR-2004-0008-0044.

[2] Partridge, R., "Petro-Seal for Ultra-low Fuel Permeation; Evaporative EPA Emissions from Boat Fuel Systems," Arkema, Presentation at the 2004 International Boatbuilders' Exhibition and Conference, October 25, 2004, Docket EPA-HQ-OAR-2004-0008-0252.

[3] Bauman, B., "Advances in Plastic Fuel Tanks," Fluoro-Seal International, Presentation at the 2004 International Boatbuilders' Exhibition and Conference, October 25, 2004 Docket EPA-HQ-OAR-2004-0008-0036.

[4] Chambers, J., "Marine Fuel Containment… A Permanent Solution," Engineered Composite Structures, Presentation at the 2004 International Boatbuilders' Exhibition and Conference, October 25, 2004 Docket EPA-HQ-OAR-2004-0008-0037.

[5] "Stopping Vehicle Fires & Reducing Evaporative Emissions: The Need to Control Gasoline & Alcohol Blend Volatility," Center for Auto Safety, March 1988, Docket EPA-HQ-OAR-2004-0008-0330.

[6] Tschantz, M., "Summer Test Program Carbon Analysis," Meadwestvaco Corporation, Presentation at the 2005 International Boatbuilders' Exhibition and Conference, October 20, 2005 Docket EPA-HQ-OAR-2004-0008-0290.

Appendix A – Basic principles of Infrared thermal imaging[1]

IR TEMPERATURE BASICS

Temperature is a measure of the thermal energy contained by an object; the degree of hotness or coldness of an object is measurable by a number of means and is defined by temperature scales. Temperature, in turn, determines the direction of net heat flow between two objects.

There are three modes of heat transfer, conduction, convection and radiation. All heat is transferred by means of one or another of these three modes, infrared thermography is most closely associated with radiative heat transfer, but it is essential to understand all three in order to comprehend the significance of IR Thermograms.

CONDUCTIVE HEAT TRANSFER

Conductive heat transfer is the transfer of heat in stationary media. It is the only mode of heat flow in solids, but can also take place in liquids and gases. It occurs as a result of atomic vibrations and (in solids) and molecular collisions (in liquids). Whereby energy is moved, one molecule at a time, from higher temperature sites to lower temperature sites.

CONVECTIVE HEAT TRANSFER

Convective heat flow takes place in a moving medium and is almost always associated with transfers between a solid and a moving fluid (such as air). Free convection takes place when the temperature differences necessary for heat transfer produce density changes in the fluid and the warmer fluid rises as a result of increased buoyancy. Forced convection takes place when an external driving force, such as a cooling fan, moves the fluid.

RADIATIVE HEAT TRANSFER

Radiative heat transfer is unlike the other two modes in several respects:

- It can propagate through a vacuum
- It occurs by electromagnetic emission and absorption.
- It occurs at the speed of light and behaves in a manner similar to light

While conductive and convective heat transferred between points is linearly proportional to the temperature difference between them, the energy radiated from a surface is proportional to the fourth power of its absolute temperature. The radiant thermal energy is transferred between two surfaces is proportional to the third power of the temperature difference between the surfaces.

Thermal infrared radiation leaving a surface is called radiant exitance or radiosity. It can be emitted from the surface, reflected off a surface, or transmitted through a surface. The total radiosity is equal to the sum of the emitted component, reflected component and the transmitted component. The surface temperature, however, is only related to the emitted component.

The measurement of thermal infrared radiation is the basis for non-contact temperature measurement and IR thermography. Like light energy, thermal radiation is a photonic phenomenon that occurs in the electromagnetic spectrum. While light energy takes place in the visible portion of the spectrum, radiative heat transfer takes place in the infrared portion of the spectrum.

All target surfaces warmer than absolute zero radiate energy in the infrared spectrum. Very hot targets radiate visibly as well. IR thermal imagers measure and display images of this infrared radiated energy.

From the point of view of IR radiation characteristics, there are three types of target surfaces; blackbodies, graybodies and non-graybodies (also called spectral bodies). A black body radiator is defined as “a theoretical surface having unit emissivity at all wavelengths and absorbing all radiant energy impinging upon it” Emissivity is defined as the ratio of radiant energy emitted from a surface to the energy emitted from a blackbody surface at the same temperature. Although blackbody radiators are theoretical and do not exist in practice, the surface of most solid objects are graybodies, that is, surfaces with emissivities that are fairly constant with wavelength.

Total radiosity available to a measuring device from a target surface has three components: emitted energy, reflected energy and energy transmitted through the target surface. If the target is a blackbody emitter, it has an emissivity equal to one, and it will reflect and transmit no energy. If the target is a graybody emitter, then it will resemble a black body in spectral distribution, but since its emissivity is less than one, it may also reflect and/or transmit energy. If the target is a non-graybody emitter, it may also emit, reflect and transmit energy. Since only the emitted component is related to temperature of the target surface it becomes apparent that a significant step in making IR temperature measurements is eliminating or compensating for the other two components.

Infrared radiation from the target passes through some transmitting medium on its way to the infrared instrument. If the medium is a vacuum then there is no loss of energy, but most infrared measurements are mad through air. The effect of atmospheric gases can be ignored for short distances, such as a few meters.

HOW THE IR FLEXCAM T AND IR SNAPSHOT CAMERA’S CONVERT RADIANCE TO TEMPERATURE

The IR Flexcam T and IR Snapshot imagers correct the infrared radiance from any single point on the target surface, so as to approach the true temperature measurements at that location. To do this, it first assumes that the IR absorption of the air path between the target and the instrument is negligible. It also assumes that there is no IR energy transmitted through the target from sources behind the target. In order to correct for reflection of the ambient background it requires the operator to input the background temperature. Note that the EPA-NVFEL test cells are held at a temperature of 25C +/- 1C.

The operator also inputs the targets estimated emissivity. All the targets of interest (Mufflers/Catalysts/Heat Shields) have been painted with a high temperature flat-black paint which has a very dull matte finish. This is used to even out the emissivity of the object over the surface as well as to increase the value of the emissivity of the object. An emissivity of 0.9 was used for this project. To check the validity of the emissivity assumptions, a comparison of the surface temperature measured with the IR imager was made to a known surface temperature measured with a thermocouple. The temperatures were within 1% of agreement.

The IR imagers used for EPA’s test program have the following general specifications. They use microbolometer detectors that require no cryogenic cooling. The detector elements are square and are located in a rectangular grid. The optical path of the camera includes an appropriate band-pass filter for the temperature range of interest. The IR Snapshot Camera has a NIST traceable calibration from 10C to 1200C with accuracy of 2C or 2% of reading. The IR FlexCam has a NIST traceable calibration from 0C to 600C with accuracy of 2C or 2% of reading. The lenses for both cameras are made from germanium and are anti-reflective coated for high transmission in the temperature range of choice.

The calibration of both the IR Flexcam and IR Snapshot was repeated on January 11, 2006. Both imagers were within the manufacturer’s accuracy specifications, thus neither imager required calibration adjustment. The calibration results are presented in Tables A-1 and A-2.

Table A-1: Summary of results for the validation of temperature calibrations for the “FlexCamT” and “FLIR” imagers. Both imagers were adjusted to account for the emissivity of the temperature targets and an ambient temperature of 25°C.

		EPA IR Flexcam T	**Briggs & Stratton FLIR**	
Emissivity of Temperature Target	**Target Temperature (°C)**	**Point Temperature (°C)**	**Point Temperature (°C)**	**Average Temperature (°C)**
0.98	5	4.6	4.9	5.6
0.93	100	99.1	102	101.6
0.97	350	351.8	350	351.5
0.93	600	590.1	602	601.6

Table A-2: Summary of results for the validation of temperature calibration for the EPA “IR Snapshot” imager.

Emissivity of Temperature Target	**Target Temperature (°C)**	**Average Temperature (°C)**
0.98	5	3.51
0.98	20	19.57
0.98	37	36.44
0.98	50	49.19
0.98	75	74.18
0.98	100	98.99
0.98	240	239.8
0.98	300	301.85
0.98	350	350.88
0.98	600	594.65
0.98	700	694.06
0.98	800	793.47
0.98	900	901.97
0.98	1000	986.42
0.98	1100	1091.14
0.98	1200	1192.84

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[1] Adapted from the IR Flexcam T and IR Snapshot Operating Manuals, Infrared Solutions Inc., Plymouth, MN, 2004.

Appendix B: Emissions Results

Table B-1: Emissions summary – Class I OHV engines at low (10-20) hours.

Engine	Tested Configuration	HC+NOx (g/kW-hr)	NOx (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)
241	OEM	10.6 ± 0.5	3.0 ± 0.3	7.6 ± 0.3	313 ± 29
241	Catalyst-muffler, venturi air	3.9 ± 0.2	1.45 ± 0.2	2.5 ± 0.3	138 ± 46
255	OEM	11.2	3.2	8.0	340
255	Catalyst-muffler*, venturi air	5.0	0.7	4.3	288
2982	OEM	8.4 ± 0.5	4.4 ± 0.4	4.0 ± 0.3	161 ± 15
2982	Catalyst-muffler, venturi air**	4.9 ± 0.3	2.8 ± 0.2	2.2 ± 0.3	85 ± 10
243	OEM	13.4 ± 0.9	4.6 ± 0.3	9 ± 1	351 ± 13
243	Catalyst-muffler, venturi air***	7 ± 1	1.8 ± 0.2	5 ± 1	334 ± 50
244	OEM	11.0	1.8	9.2	517
244	Catalyst-muffler, venturi air	7.2	1.1	6.1	433
245	OEM	10.9	2.4	8.5	472
245	Catalyst-muffler, venturi air	5.6	0.6	5.0	381

Notes:
Engines 241, 255, and 2982 are from the same engine family.
Engines 243, 244, and 245 are from the same engine family
*Tubular pre-catalyst, 22cc 200 cpsi metal monolith downstream of stamped secondary-air venturi
**35 cc, 100 cpsi metal monolith, stamped secondary-air venturi.
*** Reduced substrate volume, tubular venturi.
Stamped venturis used were based on the OEM design.
"±" values represent 95% confidence intervals for a 2-sided t-test, for 3 to 4 replicate measurements.

Table B-2: Emissions summary – Class I side-valve engines at low (10-20) hours.

Engine	Tested Configuration	HC+NOx (g/kW-hr)	NOx (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)
6820	OEM	10.8 ± 0.5	2.2 ± 0.2	8.7 ± 0.6	458 ± 45
258	OEM	10.5	2.5	8.1	487
258	Catalyst-muffler, venturi air	6.7	1.2	5.5	380
236	OEM	15.2 ± .2	3.0 ± 0.8	12.1 ± 0.8	380 ± 38
236	Catalyst-muffler, venturi air	4.9 ± 0.6	0.90 ± 0.05	4.0 ± 0.7	218 ± 62
246	OEM	12.4	1.8	10.6	490
246	Catalyst-muffler, venturi air	5.6	0.8	4.8	333
248	OEM	12.0	3.0	9.0	403
248	Catalyst-muffler, venturi air	4.6	0.8	3.8	294
249	OEM	11.3	3.0	8.3	413
249	Catalyst-muffler, (no secondary air)*	6.3	0.9	5.4	351

Notes:
Engines 6820 and 258 were from the same engine family, and used identical catalyst muffler designs.
Engines 236, 246, and 249 were from the same engine family.
Stamped venturis used were based on the OEM design.
"±" values represent 95% confidence intervals for a 2-sided t-test, for 3 to 4 replicate measurements.
The catalyst-muffler for engine 6820 was not available until just prior to the initiation of field aging – emissions measurements at low-hours were not conducted.
*Rh-only catalyst

Table B-3: Emissions summary – Class I OHV and side-valve engine tested at high (>110) hours.

Engine	Tested Configuration	HC+NOx (g/kW-hr)	NOx (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)
241 (OHV)	OEM	13.4 ± 0.6	5.2 ± 0.4	8.1 ± 0.6	266 ± 9
241	Catalyst-muffler, venturi air	6.6 ± 0.2	3.2 ± 0.2	3.4 ± 0.1	180 ± 4
2982 (OHV)	OEM	10.2 ± 0.4	6.1 ± 0.4	4.1 ± 0.2	148 ± 6
2982	Catalyst-muffler, venturi air	7.0 ± 0.4	4.5 ± 0.3	2.5 ± 0.2	85 ± 6
6820 (side-valve)	OEM	15.4 ± 0.4	2.6 ± 0.5	13 ± 1	380 ± 42
6820	Catalyst-muffler, venturi air	9.4 ± 0.7	2.8 ± 1	6.6 ± 0.8	168 ± 19

Notes:
"±" values represent 95% confidence intervals for a 2-sided t-test, for 3 to 4 replicate measurements.

Table B-4: Emissions summary – Class II OHV engines at low (10-40) hours.

Engine	Tested Configuration	HC+NOx (g/kW-hr)	NOx (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)
231	OEM	7.0 ± 1	3.0 ± 0.6	4 ± 1	333 ± 60
231	EFI	6.9	3.0	3.8	308
231	EFI, catalyst-muffler	1.8 ± 0.4	0.6 ± 0.2	1.3 ± 0.5	120 ± 29
251	OEM	9.2	5.9	3.3	228
251	catalyst muffler	3.1 ± 0.3	0.9 ± 0.6	2.8 ± 0.4	245 ± 93
252	OEM	9.1 ± 0.8	7.3 ± 0.8	1.8 ± 0.2	188 ± 33
253	OEM	6.9 ± 0.4	3.0 ± 0.1	4.0 ± 0.5	380 ± 23
253	catalyst muffler	4.5 ± 0.1	0.29 ± 0.01	4.2 ± 0.1	529 ± 11
232	OEM	8.5 ± 0.5	2.25 ± 0.08	6.2 ± 0.5	475 ± 29
232	EFI	8.0 ± 0.3	4.4 ± 0.3	3.7 ± 0.6	274 ± 42
232	EFI, catalyst-muffler	2.2 ± 0.1	0.8 ± 0.2	1.4 ± 0.2	154 ± 27
233	OEM	8.1 ± 0.7	2.2 ± 0.3	6.0 ± 0.4	459 ± 24

Table B-5: Pre- and Post-catalyst emissions for a Carbureted 400cc Class II engine after 50, 300, and 500 hours of operation.

Engine	Tested Configuration	Accumulated Hours of Engine Operation	HC+NOx (g/kW-hr)	NOx (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)
142	OEM	50	6.56 ± 0.03	2.8 ± 0.1	3.74 ± 0.07	300 ± 15
142	Catalyst	50	2.5 ± 0.6	0.12 ± 0.06	2.3 ± 0.6	282 ± 47
142	OEM	300	7.27 ± 0.18	3.60 ± 0.08	3.7 ± 0.1	238 ± 4
142	Catalyst	300	3.5 ± 0.04	0.367 ± 0.002	3.15 ± 0.04	263 ± 9
142	OEM	500	9.8 ± 0.1	6.4 ± 0.2	3.4 ± 0.1	165 ± 7
142	Catalyst	500	2.8 ± 0.7	0.7 ± 0.2	2.1 ± 0.5	170 ± 26

Notes:
The catalyst tested with engine 142 is a duplicate of the unit tested within the catalyst-muffler of engine 253.

Appendix C – FMEA of Small SI Equipment and Engines