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The Impact of Future Diesel Fuel Specifications and Engine Emissions Standards on SOFC

Final Report

Date: June 29, 2004

Prepared for: US Department of Energy, National Energy Technology Laboratory

Contract Number: DE-AM26-99FT40465; Task NT50909; Sub-Task 19

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Executive Summary

Diesel Fuel Specification Trends Until 2010

Since the 1980s, diesel fuel specifications have increasingly been tightened to meet environmental objectives, in addition to ensuring compatibility with diesel engines. The most stringent current specifications, those promulgated by the California Air Resources Board (CARB), limits sulfur, aromatics, polycyclic aromatic hydrocarbons (PAH) and several other fuel impurities [1-3]. As air quality problems persist, there is continued pressure to further reduce emissions from diesel engines, and hence to further tighten diesel specifications. By 2010 (Figure 0-1), on-road diesel fuel sulfur levels will be reduced to 15 ppm (in the U.S.) or even 10 ppm [in the European Union (EU)]. Recently proposed regulations will extend these specifications to virtually all diesel fuel used in engines.

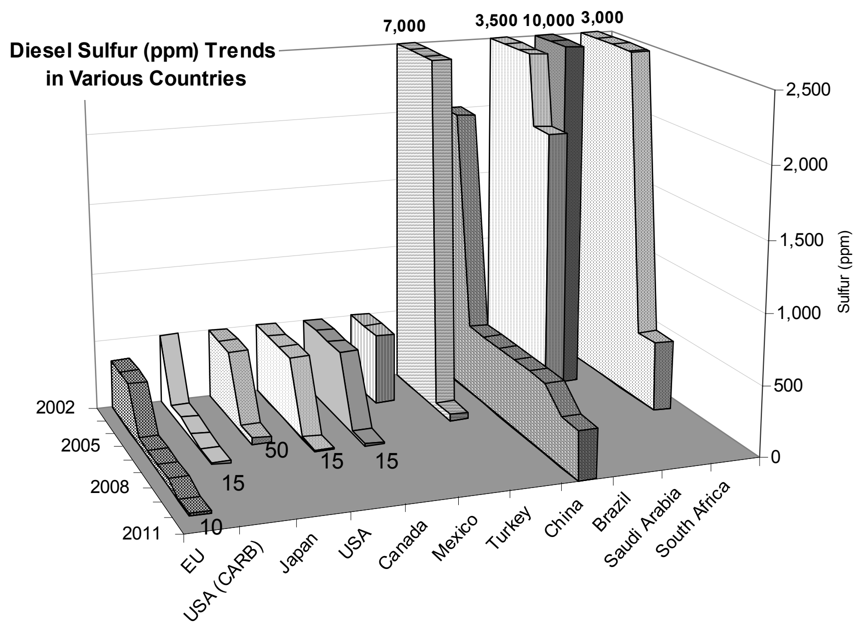


Figure 0-1 By 2010, World-wide Diesel Fuel Sulfur Will be Drastically Reduced (after [4])

In some jurisdictions, aromatics and PAH content in diesel fuel, which is strongly correlated with soot production, are also under pressure. CARB and the EU will have limits at 10% and 14% respectively [1, 5], while the U.S. federal specifications limit aromatics to 35% [6]. PAH regulations will exist in California and in Europe. The incremental cost of producing diesel that meet the US 2007 / Euro 5 standards is expected to be in the 2 to 4 cents per gallon range [2, 7].

Diesel Engine Trends Until 2010

The tightening of fuel specifications is driven by significant tightening of the engine emissions standards for compression ignition (diesel) engines. Significant reductions in oxides of nitrogen (NOx) and Particulate Matter (PM), will be required in almost all classes of diesel engines, and in most cases, requiring significant changes in powertrain technology (Figure 0-2) [8-11]. In the smaller non-road engine category (19 to 56 kW, which contains the smaller mobile generators) a 97% reduction in PM will be required under proposed EPA and EU rules (or a 25% reduction under current rules) and a 40% reduction in NO_x under proposed rules (or a 25% reduction under current rules)[12]. The proposed rules may require electronic engine controls, exhaust gas recirculation (EGR), and a diesel particulate filter (DPF), while current rules would require combustion system modifications and electronic engine controls.

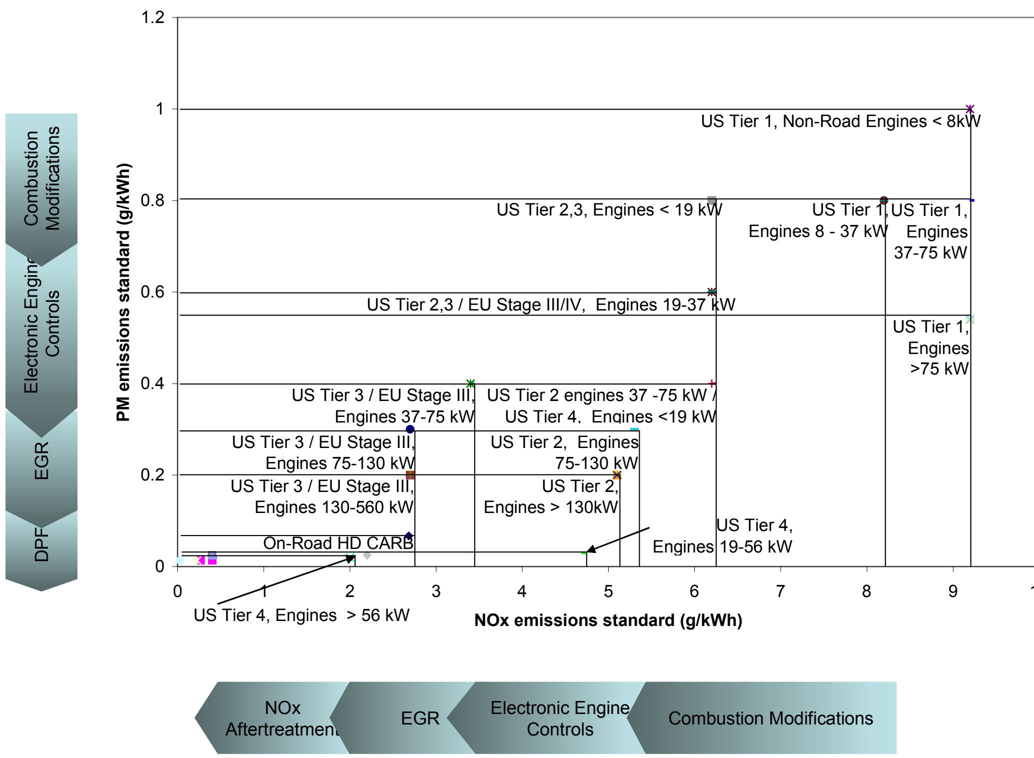


Figure 0-2 Diesel Engine Emissions Standards are Drastically Reduced by 2010

The smallest category of non-road engines [which captures many of the auxiliary power unit (APU) and remote applications] will require a 25% reduction in NOx, and a 50% reduction in PM (only under proposed EPA regulations). This will require the application of electronic engine controls and combustion system modifications [12].

While the technologies to achieve the reductions needed for these smaller engine categories are proven, the technologies needed for the more stringent regulations for larger diesel engines are still developmental, and may require trade-offs in performance, utility, and efficiency for users [10, 13].

Impact of New Fuel Specifications on SOFC

Technical Impact

The changes in diesel fuel specifications can be expected to lower some of the hurdles in the development of diesel solid oxide fuel cells (SOFC), avoiding an additional estimated 2 to 3 year delay in its commercial introduction. The biggest technical impact on system development results from the reduction in sulfur content. The reduction of diesel fuel sulfur to about 15 ppm will dramatically reduce the level of sulfur-tolerance required for reformer catalysts, and reduce the anode-feed gas-phase sulfur concentration to the same level as that experienced when using pipeline natural gas as a fuel. The specific effects expected are:

- Anode sulfur levels will still be too high if uncontrolled for conventional anodes () [14-16], especially if the stack is operated at lower temperatures;
- Chances of development of advanced anodes with sufficient sulfur-tolerance are significantly improved;
- If sulfur removal systems are still required, cartridge or bed replacement intervals will likely be stretched to more than the targeted stack life (more than 40,000 hours);
- Reformer sulfur tolerance requirements will be reduced, making it plausible that sulfur-tolerant reformer catalysts will be successful;
- If the stack is operated at lower temperatures, and the sulfur is uncontrolled, anode sulfur levels will still be too high for conventional anodes (4) [14-16].

In each of these system components, lower aromatics content would provide greater flexibility in design and operating conditions. The main impacts of this will likely be slight increases in system efficiency, and a significantly improved reliability. However, given the modest changes in aromatics and PAH content resulting from the move to ultra low sulfur diesel (ULSD), the overall impact of lower aromatics on SOFC system performance and cost is most likely trivial when compared to the cost and performance impacts resulting from the reduction in sulfur content.

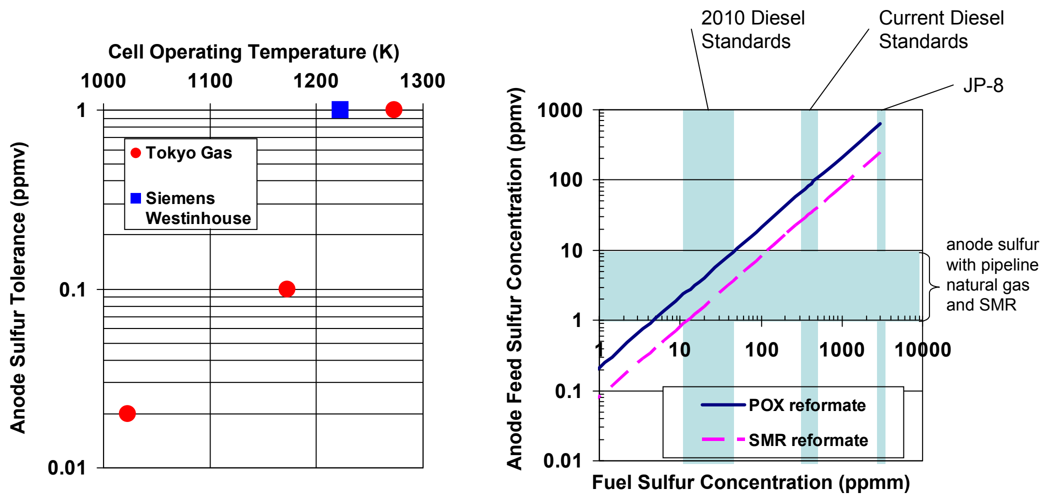


Figure 0-3 Sulfur Tolerance of State-of-the-Art SOFC Anodes and Sulfur Concentration in Anode Feed as a Function of Fuel Concentration

Cost Impact

Based on a 2001 study by Arthur D. Little (ADL) [17] in which system designs and cost estimates for SOFC APU systems were made when operating on reformulated gasoline (with sulfur) and sulfur- and aromatics-free diesel fuel, and taking into account the abovementioned effects of the change from CARB Diesel to ULSD, we develop a sense of the maximum impact of new diesel fuel on SOFC system cost (Figure 3-5) and efficiency. As in the ADL study, the effect of lower sulfur will likely be marginal. The more significant effect is an approximately 10 liter reduction in system volume, resulting from the elimination of the sulfur trap.

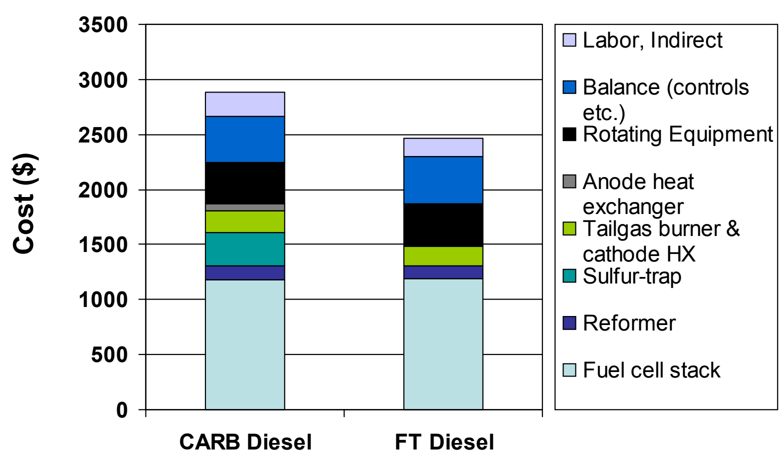


Figure 0-4 Estimated Impact of Change from CARB Diesel to Zero Sulfur, Zero Aromatics Fuel on Manufactured Cost of 5 kW SOFC APU(after [17])

Because all fuel contaminants are either eliminated or converted before the tail gas burner, we do not expect to see any change in emissions from SOFC systems associated with the changing diesel fuel specifications.

Impact on National Benefits

Overall, the potential national emissions benefits of diesel SOFC in the selected four markets is reduced by up to 40% by the introduction of new diesel regulations, while the energy savings benefits are increased by up to 15%. These benefits depend on the application and especially on the engine capacity. Because of changes in the classification, some categories see a 90% reduction in PM emissions benefits while others see no change at all.

The cost increase of diesel engines in the smaller size category that is expected to be associated with meeting the new diesel regulations are expected to range from about \$15 to \$45 per kW (the higher numbers are for larger capacity equipment which has to meet the more stringent standards) [12].

Conclusions and Recommendations

Conclusions

As most diesel fuel sold in the U.S. and Europe will be ULSD (with 10 to 15 ppm sulfur) by 2010, the development of diesel SOFC technology will be accelerated, even though the need for more sulfur-tolerant reformers and anodes will remain. In addition, the analysis indicated that the lower sulfur content in diesel will virtually eliminate the cost-penalty for diesel-SOFC (which may be about \$100 per kW if CARB diesel were to be used). The analysis indicates that diesel SOFC designed for ULSD will be substantially the same as one designed for operation with reformulated gasoline. This could substantially broaden the appeal of SOFC compared with diesel engines. The competitive position of SOFC is further strengthened as emissions control technology will drive engine cost up by \$15 to \$45 per kW [12]. The impact on SOFC efficiency and engine efficiency is expected to be modest.

Our analysis shows that combined, these impacts of the new diesel regulations on both SOFC and engines have several consequences for the national impacts of the use of diesel SOFC in selected small-capacity (less than 56 kW) SOFC applications (including APUs, mobile generators, remote telecoms and industrial power, and small non-road vehicles):

- The criteria pollutant emission benefits from SOFC are reduced as the engines that they replace become substantially cleaner. Still, SOFC will be substantially cleaner than the competing engine technologies;

- The reductions in energy use and greenhouse gas emissions that result from the use of diesel SOFC are maintained and in some cases increased;
- The cost comparison between high duty cycle diesel engines (i.e. not stand-by generators) and diesel SOFC will change in SOFC's favor due to the new regulations.

There remains considerable uncertainty, as well as considerable challenges in the implications for military applications. There will be a growing discrepancy between JP-8 specifications (there is no plan to change those) and those for civilian diesel fuels, resulting in the incompatibility of JP-8 with most civilian diesel engines and most civilian SOFCs. Several groups within the Department of Defense (DoD) have started to address this challenge.

Recommendations for DOE

Although DOE's Solid State Energy Conversion Alliance (SECA) program is already well-positioned to help prepare the SOFC industry for the 2010 diesel regulatory situation, there are additional actions that could be taken to focus the program even better on the future regulatory situation:

- Development work on advanced anodes should focus on the most relevant anode-gas sulfur levels: 1 to 5 ppm for ULSD systems, 100 ppm for systems to operate on conventional diesel and 1000 ppm for systems that operate on JP-8;
- Several basic parametric studies combining experiment with analysis could accelerate both materials and stack development by better characterizing the impact of detailed fuel composition and operating conditions on SOFC stacks. A minimum standard for characterization of fuel impact could also be implemented for all stack and cell development efforts.

1 Background and Objectives

Background

Key to the SOFC's potentially broad appeal is the ability to build SOFC systems for use with a wide variety of widely available fuels, including diesel fuel. For many remote, mobile and military applications the use of diesel fuel (or similar fuels such as JP-8) is highly desirable or even required. If a highly efficient, clean, and low-cost diesel-fueled SOFC technology is developed successfully, it could find a very wide range of applications, perhaps even broader than that of internal combustion engines. Applications would include stationary power generation from the kW-scale to utility-scale, mobile applications such as providing auxiliary power for vehicles, a wide range of military applications of various kinds, and ultimately perhaps motive power for certain transportation applications.

Unfortunately, current SOFC technology poorly tolerates certain components of and impurities in diesel fuel such as aromatic hydrocarbons and sulfur [15, 16]. Because specifications for diesel fuel have been developed to make it universally compatible with compression ignition engines (CIEs), the use of diesel fuel in SOFC represents several challenges compared to operating with lighter fuels such as gasoline or natural gas, including:

- The high sulfur levels currently allowed (between 150 and 500 ppm in the developed world, higher in developing countries) can lead to poisoning of the reforming catalysts or of the anode's electrocatalysts, as well as to corrosion;
- The high content of aromatics, naphthenes and other ring-compounds can lead to soot or carbon formation in the reformer, the fuel cell, or other parts of the system. This carbon eventually disrupts SOFC operation and can cause unacceptable emissions.

SOFC development programs such as the DOE's SECA program have focused considerable resources on ensuring that future SOFC technology will be compatible with diesel fuel. Such programs include work on improved sulfur tolerant anodes and some DoD programs have aimed at producing a prototype system that operates on diesel fuel or its equivalent.

These same fuel properties that challenge SOFC developers lead to high emissions when used in CIEs. To reduce CIE emissions consistently with environmental requirements, advanced CIE aftertreatment technologies will be required, especially for the control of NOx. To enable such technologies, regulators in the U.S., Europe, Japan, and other countries are gradually tightening fuel specifications for diesel fuel, limiting the amount of sulfur to 10 to 15 ppm, and in some cases limiting diesel aromatic and PAH content at the same time. In addition, also to spare the environment, regulators in some markets will introduce regulations that will restrict CIE use (such as idling restrictions.) Such drastic improvements in diesel fuel quality can impact SOFC in several ways, including:

- Cleaner diesel will make it easier to make SOFC technology compatible with diesel fuel. This could have implications for the SECA program as well as for the timing of market introduction of diesel-powered SOFC;
- Cleaner diesel and the accompanying CIE emissions control technology will dramatically reduce the emissions from CIEs and increase their cost, which may impact the competitive position of SOFC;
- Idling restrictions and other CIE use regulations may also impact SOFC competitive positioning, generally favoring SOFC.

Objectives and Scope

As regulations will drive considerable changes in diesel fuel specifications until 2010 DOE has recognized that it needs to understand the potential impact of these changes on the technical feasibility, research and development needs, and competitive positioning and benefits of SOFC. Specifically, DOE wanted to:

- Characterize the relevant diesel specifications and related regulations with respect to their timing and effect on diesel fuel and its uses. These should include:
    - Fuel specifications applicable for 2010 (this includes the 2006/7 national ULSD specs for the U.S., as well as the Euro V specifications for Europe) and relevant military specifications, and in contrast to current California (CARB) specifications;
    - CIE regulations expected to be in place for the relevant markets by 2010, including a review of uncertainties in the regulations. This would include regulations for over-the-road vehicles as well as off-road vehicle applications, idling regulations for trucks, and any relevant regulations for stationary and military markets;
- Evaluate and quantify possible effects on the SECA program technology targets, timing, and likelihood of success;
- Evaluate and quantify possible effects on the market size and benefits to the nation of the SECA program, considering the impact on both diesel-fueled SOFC technology and CIE technology.

To focus the analysis, the report concentrates on the following potential SOFC applications:

- APUs for trucks, yachts, and RVs;
- Telecoms and other industrial applications;
- Mobile generators;
- Non-road vehicles;
- Military applications, including vehicle APUs and mobile power.

2 Diesel Regulation Trends Until 2010

Background and Overview

In the early 1900s, diesel fuel standards were first developed to ensure that diesel engine owners could buy a fuel that was compatible with the requirements of their engines. To achieve this, these early standards controlled primarily the distillation and boiling ranges, the fuel's lubricity, its cold-flow properties, and its cetane number. Currently these diesel standards are embodied in standards such as ASTM D975-93, and its equivalents under European and Japanese normalization organizations. In the U.S., as in many other jurisdictions, several basic grades of diesel fuel are in use (in addition to various low-sulfur variations):

- No. 1 Diesel Fuel - A special-purpose, light distillate fuel for automotive diesel engines requiring higher volatility than that provided by Grade Low Sulfur No. 2-D;
- No. 2 Diesel Fuel - A general-purpose, middle distillate fuel for automotive diesel engines, which is also suitable for use in non-automotive applications, especially in conditions of frequently varying speed and load;
- No. 4 Diesel Fuel - A heavy distillate fuel, or a blend of distillate and residual oil, for low- and medium-speed diesel engines in non-automotive applications involving predominantly constant speed and load.

In this report we will further focus on No. 2 diesel, since it is by far the most common type of diesel fuel, and hence the diesel fuel grade of most interest to fuel cell developers.

Since the 1980s, diesel fuel specifications have increasingly been tightened to meet environmental objectives, controlling concentrations of major fuel constituents (aromatics and polyaromatics), as well as impurities (mainly sulfur and nitrogen.)

The tighter fuel specifications and accompanying engine specifications have however been deemed insufficient to achieve the environmental objectives and hence many countries continue to tighten specifications. Historically, the emissions from diesel engines have been much less stringently regulated than those from gasoline engines. This difference results from a number of factors, including the technical difficulty in reducing emissions of particulate matter and nitrogen oxides from diesels and the recognition by regulators that diesel engines are highly efficient when compared with gasoline engines. However, as many regions around the world continue to struggle to meet basic ambient air quality standards, and as emissions reduction from gasoline engines and other sources has been pushed, emissions standards for diesel engines is receiving renewed attention. Most countries are now proposing stringent new regulations which would substantially close the gap in emissions standards between diesel and gasoline engines.

Historically diesel fuel specifications and diesel engine emission standards have varied considerably by geographic region, application, and engine size, but by 2010 many of these standards will be more or less harmonized. This harmonization is a result of the interest of fuel and engine industries to be able to produce standard products world-wide and the regulators' drive to regulate emissions close to the limits of what is technically possible.

This chapter first reviews diesel fuel specifications, and subsequently the accompanying diesel engine emission standards for the U.S., Europe, and for NATO military markets.

Changes in Fuel Specifications

The most stringent specifications for diesel fuel are those that apply to fuel used in on-road vehicles. This also represents the majority of diesel fuel used (Figure 2-1) [18]. Distillate fuel used in stationary applications is usually referred to as fuel oil (#2 fuel oil in the U.S.) and faces far fewer regulatory requirements. Specifications for diesel fuel used in non-road applications (including off-highway diesel, certain military uses, farm, railroad, and vessel bunkering) usually follow those set for on-road with a sometimes significant time delay. The following chapter focuses on the specifications for on-road fuels. The corresponding non-road standards are as follows [12]:

- Current non-road standards correspond to pre-1993 on-road standards, no sulfur limits are imposed and the average sulfur level is about 3,400 ppm;
- After 2007, proposed Tier 4 EPA regulations would require non-road diesel to comply with the same specifications that currently apply to on-road diesel fuel (500 ppm sulfur limit);
- After 2010, proposed Tier 4 EPA regulations would require non-road diesel fuel to comply with the same specifications as on-road ULSD, required for on-road applications after 2006 (limit 15 ppm sulfur).

European regulations follow a similar trend.

Non-road diesel engines sometimes use on-road diesel fuel for convenience. For example APUs, which are classified as non-road diesels, share the fuel tank with the main engine, which must use on-road diesel.

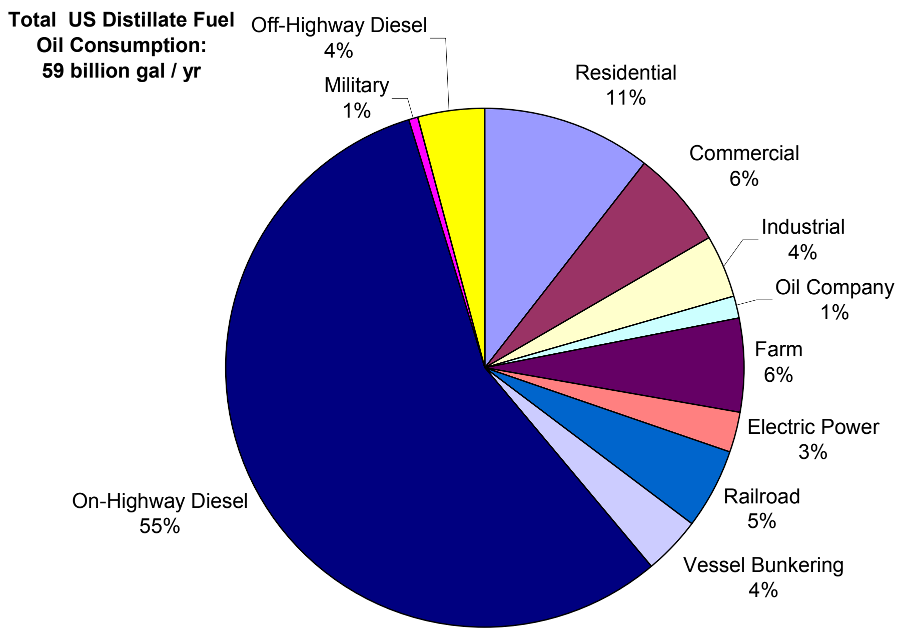


Figure 2-1 US Annual Fuel Oil Consumption in 2001 (Source EIA [18])

Current Diesel Fuel Specifications

As the baseline for this study we use the current California Air Resources Board (CARB) diesel fuel specifications [1]. These specifications are based on U.S. federal diesel specifications and were first introduced in 1993. The CARB specifications differ from the federal specifications by limiting aromatic, polyaromatic hydrocarbon, and nitrogen content and requiring a slightly higher cetane number. These more stringent specifications support California's State Implementation Plan to comply with the National Ambient Air Quality Standards (NAAQS), mainly to limit particulate matter and hydrocarbon emissions. The CARB diesel specifications offer fuel producers two options:

Meet the reference fuel specifications (

- Table 2-1.) As can be seen, small refiners are allowed to produce sulfur with higher aromatics content but must still meet the same sulfur content as large refiners;
- Produce an alternative fuel formulation and demonstrate (through emissions testing with standard engines) that the emissions impact is the same as or better than that achieved with the reference fuel.

Table 2-1 Overview of CARB DF2 (on-road) Reference Fuel Specifications [1]

Property	ASTM Test Method	CARB General Reference Fuel Specifications	CARB Small Refiner Reference Fuel Specifications	U.S. Federal Specifications
Environmental Specifications				
Sulfur Content (ppm, Wt)	D2622-94	500 max	500 max	500 max
Aromatic Hydrocarbon Content (Vol %)	D5186-96	10% max	20% max	35% max
Polycyclic Aromatic Hydrocarbon Content (Wt %)	D5186-96	1.4% max	4% max	Not specified
Nitrogen Content (ppm, Wt)	D4629-96	10	90	Not specified
Engine Operation Specifications				
Natural Cetane Number	D613-84	48 min	47 min	40 min
Gravity, API	D287-82	33-39	33-39	33-39
Viscosity at 40°F, cSt	D445-83	2.0-4.1	2.0-4.1	2.0-4.1
Flash Point, °F (min.)	D93-80	130	130	130
Distillation, °F	D86-96			
IBP		340-420	340-420	340-420
10% Rec.		400-490	400-490	400-490
50% Rec.		470-560	470-560	470-560
90% Rec.		550-610	550-610	550-610
EP		580-660	580-660	580-660

Since the introduction of these fuels, California diesel fuel has been substantially cleaner than average U.S. fuel (Table 2-2.) As many refiners have chose to produce and prove alternative diesel fuel formulations, aromatics content in California is higher than that specified in the reference fuel standards. This is off-set by substantially lower sulfur content. It is noteworthy that currently an estimated 20% of California's fuel already had less than 15 ppm sulfur (this includes gasoline.) In addition to the trade-offs made in producing alternative diesel fuel formulations, natural overshoot is also partially responsible for the fact that actual sulfur levels are lower than the regulated limits.

California has resolved to harmonize its diesel fuel standards with federal standards as the 2007 U.S. federal standards are phased in. It is still considering the possible need for additional alternative diesel fuel initiatives to meet the NAAQS. In addition, as part of California's diesel risk reduction plan, it is considering how to further reduce diesel impact on emissions of hazardous air pollutants.

Table 2-2 Impact of CARB Regulations on Diesel Fuel Constituents and Impurities [3]

Specification	California		U.S.[1]
	Pre-1993	**2001**	**Current**
Aromatics (vol %)	35	19 – 22	35
Sulfur, ppmw	440[2]	140[3]	360
Cetane No.	43	50 – 52	45
PAH	ND	3	ND
Nitrogen	ND	150	110

Future Trends in Diesel Specifications

The most significant change expected in diesel fuel specifications between now and 2010 is a substantial reduction in sulfur content. In the U.S. sulfur levels will be reduced to 15 ppm (Wt.) [6] while Europe [4, 5] and Japan will be requiring 10 ppm (Wt.) In the mean time many other countries are tightening diesel fuel sulfur specifications to around 500 ppm [19], while still other countries are contemplating joining the U.S. and Europe in moving to 10 to 15 ppm standards.

Another general trend is a harmonization of diesel fuel specifications around the world, and across application markets. Currently certain categories of non-road diesels are allowed to use fuels that do not have to meet the most stringent sulfur and aromatics specifications. By 2010, it appears that diesel specifications will be very similar for all applications and around the world. This harmonization is driven by recognition of the economic disadvantages of having an infrastructure for a wide range of fuel specifications, and by the fact that in order to meet tight emissions standards, both fuels and engines will be pushed to their technical limits.

Sulfur Specifications

By 2010, diesel fuel sulfur levels will be reduced to 10 to 15 ppm in the U.S., Europe and Japan (Figure 2-2.) Starting in 2006, the U.S. and Canada will ramp-down levels rapidly from current levels (500 ppm) with a goal of reaching 15 ppm in 2008. EU standards will be reduced from the current 350 ppm to 10 ppm in the period between 2004 and 2010 (including an intermediate 50 ppm level required in 2006.) It is also especially noteworthy that such specifications will likely apply equally to on-road

[1] AAMA National Fuel Survey
[2] For Los Angeles area, > 3,000 ppmw in rest of California
[3] About 10 – 20% of California volume is < 15 ppmw
ND = no data available

and non-road use of diesel fuel, whereas today non-road diesel engines are often exempted from the current specifications and regulations for on-road diesels.

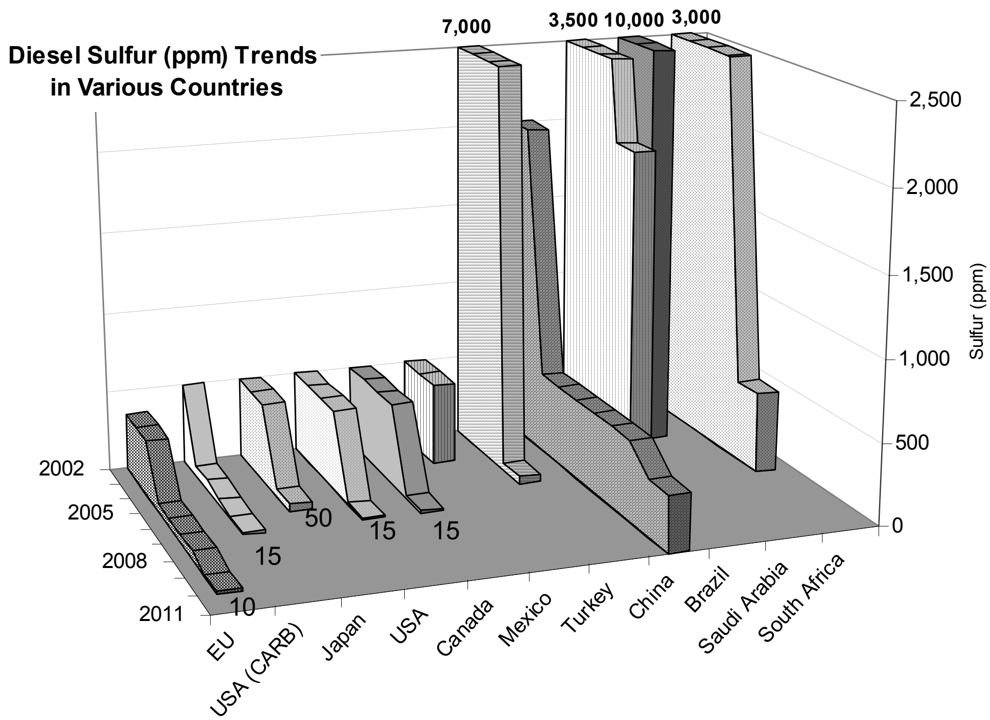


Figure 2-2 Diesel Fuel Sulfur Specification Trends in Various Countries (Source: IFQC [4])

Figure 2-2 clearly shows that in most of the developed world, diesel fuel sulfur levels will be regulated down to 10 to 15 ppm by 2010. EU regulations are shown to reach the 10 ppm level by 2011, but several efforts are under way to accelerate introduction to achieve complete compliance by 2008 for on-road as well as non-road fuels. In addition, many of the EU member states are introducing ULSD significantly earlier. In Sweden, 10 ppm sulfur has been mandatory for several years, while many others have already moved down to 50 ppm; well ahead of the 2006 EU deadline [20] (Figure 2-3.) Other countries not shown on the chart such as Australia and New Zealand will follow either U.S. or European regulations. In addition, some prospective entrants to the EU, such as Turkey, will have to meet EU standards also.

Many of the other countries in the world with high diesel consumption, such as China, India, and Russia, will move to standards similar to those now in place in the U.S. and Europe. Some of these countries, especially in the Far East, are currently contemplating a more drastic ratcheting down of standards which would bring them on par with the U.S. and Europe by 2010.

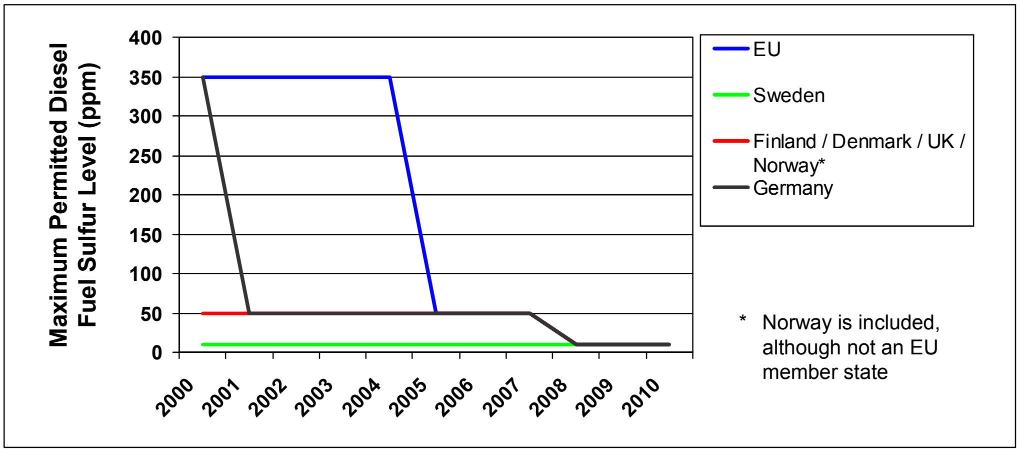


Figure 2-3 Sulfur Standards for EU and Selected EU Member States (Source: [20])

Still other countries, especially in central Asia (e.g. Afghanistan) and Africa, there are no plans for tightening diesel fuel sulfur specifications. With current diesel fuel sulfur levels at between 3,000 and 10,000 ppm, or non-existing altogether.

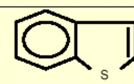
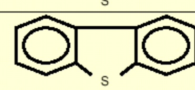
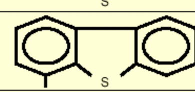
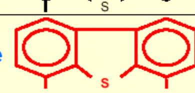
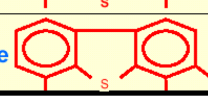
Reaction Compound		Relative Rate	Boiling Point
Thiophene		100	185°F
Benzothiophene		30	430°F
Di-benzothiophene		30	590°F
Methyl-di-benzothiophene		5	600 – 620°F
Di-methyl-di-benzothiophene		1	630 – 650°F
Tri-methyl-di-benzothiophene		1	660 – 680°C

Figure 2-4 Overview of Reactivity of Various Sulfur-Containing Diesel Species on State-of-the-Art Desulfurization Catalysts (From: [21])

The technologies used by refiners to remove sulfur from diesel fuel down to ULSD levels typically is least effective in reducing sulfur in so-called sterically hindered dibenzothiopenes and similar species, relative to benzothiophenes and mercaptans (Figure 2-4.) Such refractory species are thus virtually the only ones remaining in less than 15 ppm diesel fuel. Unfortunately, such species are also the hardest to remove with desulphurization systems. The implications of such a shift are discussed in Chapter 3.

Aromatics Specifications

While aromatics specifications for diesel fuel vary much more widely than those for sulfur, considerable reductions in aromatics content can be expected in many markets between now and 2010. Aromatics in diesel fuel are considered to have a strong impact on soot emissions. In fact several studies have suggested that soot emissions from a diesel fuel used in both controlled and uncontrolled diesel engines are proportional to the aromatics content of the fuel. This is even more clearly the case with PAH (sometimes referred to as PNA or PACs). Soot emissions from diesel engines have come under increased scrutiny because small particulates (so-called PM 2.5 and PM 10) are increasingly implicated in a variety of common diseases such as asthma and lung-cancer and diesel engines are among the main sources of such small particulates. The regulatory response is to require the use of particulate filters and the regulation of aromatics and PAH levels in diesel fuel.

Since aromatics are a substantial component of diesel fuel refined from crude oil, and cannot be converted into other diesel components easily and without considerable use of energy and hydrogen, elimination of aromatics is not an option in most cases. CARB's reference fuel contains 10% aromatics and 1.4% PAH. This requirement is one of the main reasons for refiners to produce an alternative diesel fuel, in which slightly higher aromatics content is traded off against lower sulfur content in the fuel.

Europe is the only major market in which regulations are in place that will drive down aromatics content by 2010 (Table 2-3.) While U.S. specifications will not change, it is likely that aromatics content of diesel fuel will still go down somewhat as a side-effect of stricter sulfur standards.

- In California, those producers that currently have opted to trade-off higher than reference fuel aromatics against lower sulfur will no longer be able to do so. Even if they could further reduce sulfur, the effect on particulates emissions is unlikely to be sufficient to off-set higher aromatics.
- In general, as some refiners will use a form of hydrodesulfurization or similar technology to achieve the low sulfur standards, inevitably some of the aromatics and polyaromatics will be hydrogenated too (probably largely into cyclobenzenes and naphthenes).

Overall though aromatics content will be affected much less drastically than sulfur content of diesel fuels by new fuel specifications to be introduced between now and 2010. In other regions in the world, much less stringent aromatics standards are in place while other regions have no aromatics standards in place at all.

Table 2-3 Aromatics and Cetane Standards for U.S. and European Diesel Fuels for 2010 (Source: [9])

Property	US EPA	US CARB	EU
Aromatics Content (% vol)	35%	10 / 20 %	15%
PAH Content (% wt)	NS	1.4 – 4%	2%
Cetane Number	40	48	51

Finally, Table 2-3 also shows the cetane number of the diesel fuels. The cetane number is a similar characteristic to the octane number used for gasoline and reflects the ignition delay in a standard test engine (higher cetane number means shorter ignition delay.) Specific engines require a minimum cetane number for smooth normal operation. Higher cetane numbers do not improve steady state operation of a given engine but improves cold-start performance, and provides engine designers with more freedom especially in designing high-speed, high-performance diesel engines. That is why CARB and the EU are requiring higher cetane numbers. In addition, diesel fuels with higher cetane numbers usually correspond to higher hydrogen content and higher aliphatics content than diesel fuels with lower cetane numbers. Higher hydrogen and aliphatics content, like lower aromatics, will tend to reduce carbon formation and reduce flame temperatures.

Cost Implications of New Standards

The incremental cost of producing diesel that meet the US 2007 / Euro 5 standards is expected to be in the 2 to 4 cents per gallon range. A number of recent studies analyzing the potential additional cost of producing ULSD were summarized this year by CARB. The results are shown in Table 2-4. Cost related to the de-sulfurization process represents the largest portion of this increase, but the distribution system upgrades and the cost of lubricity additives can also be considerable. It is noteworthy that if the sulfur level further reduced below 10 to 15 ppm, the cost of the distribution system upgrades would escalate because it would preclude fuel companies from using shared distribution systems for ULSD and other products.

Table 2-4 Expected Additional Cost to Produce ULSD (Source: [2, 3]]

Cost Component	Range (¢ /gallon)
Refinery desulfurization (capital and O&M)	2.2 – 2.7
Distribution System	0.0 – 0.2
Lubricity Additives	0.2 – 0.4
Fuel Economy Penalty	0.0 – 0.5
Total	2 – 4

Military Fuel Specifications

Over the past decade, the U.S. military, as well as those of other NATO members, have been moving to standardize the fuels for diverse battlefield and civilian needs. To simplify the logistics management, a special derivative of kerosene was formulated (referred to as JP-8 or NATO F-34) which can fuel diesel engines, gas turbines, and heating systems. JP-8 can be used interchangeably with #2 Diesel Fuel (DF2) in the military's diesel engines, which are based on civilian production engines [22].

One key objective of the JP-8 specification is to ensure maximum availability in potential battlefield locations. Therefore, specifications had to be consistent with capabilities of many refineries that do not typically serve the U.S., Europe, or Japan. As a consequence, the specifications of the fuel are rather relaxed, compared even with current CARB fuel or even federal DF2 specifications:

- Maximum sulfur levels are 3,000 ppm (compared to 500 ppm for CARB diesel.) This is both to ensure compatibility with overseas refining capabilities and also because the sulfur species provide needed lubricity for some engine applications (especially turbines);
- No maximum aromatics content (compared to 10% and 35% for CARB and U.S. federal diesel respectively.) Kerosene aromatics levels can be as high as 60%.

In the U.S., the military received an exemption from the EPA which allows it to use JP-8 in on-road vehicles, even though it does not strictly meet federal DF2 standards. To receive this exemption the military had to prove extensively that, largely because actual U.S. JP-8 rarely exceeds DF2 specifications, such use of JP-8 by military vehicles on U.S. highways does not lead to worse air pollution than the use of DF2 by similar vehicles.

The emergence of 2007 U.S. (and Euro 5) fuel specifications and vehicle technology presents the NATO militaries with a dilemma: will they modify the specifications of JP-8 to ensure complete interchangeability with ULSD in conventional diesel engines or will they have to accept ULSD as a separate fuel for its low-emissions diesel engines and vehicles. The considerations include:

- By 2007, all civilian U.S. on-road vehicles will have emissions control technology that will be incompatible with high-sulfur fuel (let alone 3,000 ppm sulfur JP-8). The U.S. military want to make maximum use of civilian technology to reduce the cost of engines and vehicles, but they will be incompatible with the single battlefield fuel;

- If the military switches to ULSD and 2007 civilian engine technology for some of its vehicles, these vehicles may not be usable in battlefield situations in some countries where ULSD is not available, unless a separate ULSD supply chain is created for these vehicles;
- The military may have to prove again to EPA that its use of JP-8 in military vehicles does not compromise the environment. If JP-8 sulfur is not reduced and 2007 engine technology is not used, the military is unlikely to be able to prove this, and hence it might be prohibited by EPA to use JP-8 for on-road vehicles in the U.S., with or without emissions control technology.

Some European militaries reportedly are already considering the use of ULSD and a separate fuel infrastructure for on-road vehicles.

Alternative Diesel Fuels

In addition to the new petroleum-based diesel fuel formulations that are driven by new regulations, a number of parties are moving to introduce a range of diesel fuel alternatives. All of these alternatives aim to reduce the environmental impact of diesel fuel use. The economics and viability of the different alternatives undoubtedly vary dramatically, but nevertheless some of them may become relevant for fuel cells by 2010. Two alternatives reviewed here are GTL diesel and biodiesel.

Several major oil companies are poised to commercialize large-scale gas-to-liquids technology, which uses a variant on Fischer-Tropsch synthesis to chemically convert natural gas to ultraclean diesel fuel. GTL diesel (as produced) is completely free of sulfur and aromatics, and has a cetane number of 77. As such in its pure form GTL diesel is considered an ideal fuel for both advanced diesel engines with advanced emissions control technology and for fuel cells. Given that estimated worldwide GTL diesel production will probably not exceed 150,000 barrels per day by 2010 (equal to a large petroleum refinery); GTL diesel will probably be blended with conventional diesel.

Especially in Europe, there is much interest in the use of biodiesel, a diesel-substitute made through transesterification of vegetable oil. Biodiesel is renewable and could lead to a reduction in particulate emissions from diesel engines, however NOx emissions will likely increase. Despite serious concerns from engine manufacturers about the stability and economy of biodiesel, the EU is providing significant support for the fuel because of its potential to reduce greenhouse gas emissions. Biodiesel also has a very different chemical structure compared with conventional diesel, containing much more oxygen. Though it does not contain high concentrations of aromatics, it contains other cyclic species with a similar effect and it still contains sulfur.

Changes in Diesel Engine Emission Standards

The primary competition for diesel fueled-SOFCs is traditional diesel engines. Hence it is critical to understand the impact of new emissions standards on the performance, efficiency, and cost of future diesel engines.

Engine Classifications

For regulatory purposes diesel engines in most jurisdictions are classified into the broad categories described in Figure 2-5. The reasons for the distinctions between the classes is to allow appropriate regulation of applications with engine capacities ranging from 1 to over 10,000 kW, and with duty cycles of between a few hours per year to continuous duty.

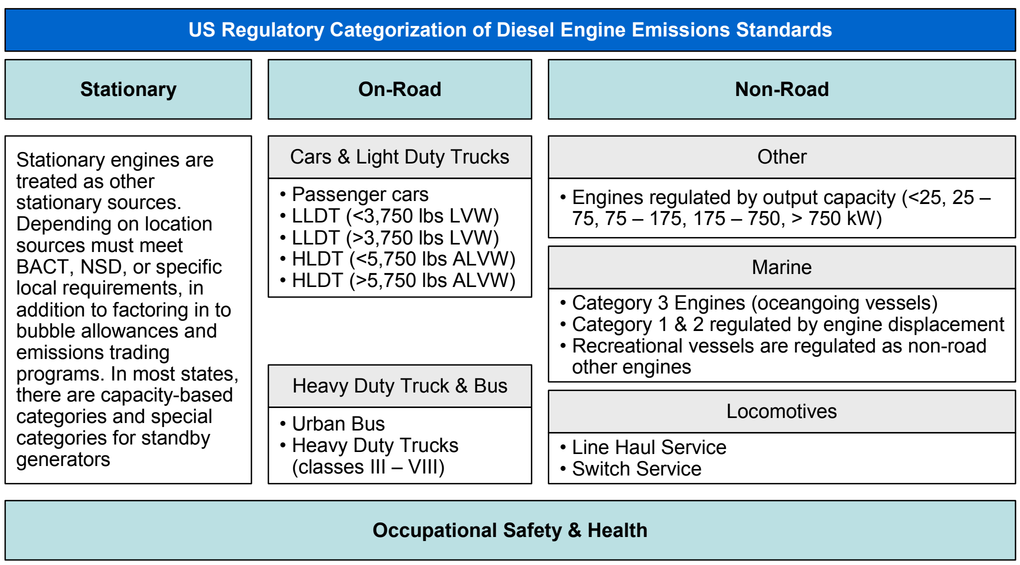


Figure 2-5 US Regulatory Categorization of Diesel Engine Emissions Standards

While by far most of the regulatory attention for diesel engines has been devoted to on-road diesels, these are not likely to be the most relevant engines from the SOFC developers' point of view. Diesel engines for on-road vehicles it is the largest category based on aggregate annual fuel consumption which explains the regulatory focus. Typically, on-road diesel engines are further classified into light duty engines (cars and light duty trucks) and heavy duty engines (trucks and buses.) In the jurisdictions under study here light duty engines are regulated as part of the vehicle (similar to gasoline engines) while heavy duty engines are regulated as powertrains separately.

Most SOFC developers have activities aimed at APUs for trucks, buses, and recreational vehicles, applications which are typically regulated as non-road diesel engines. While considerably more complex in regulatory structure, non-road diesel engines are also receiving regulatory attention. EPA and the European Parliament both proposed an extension of US 2007 and Euro 5 standards to all but the smallest non-road diesel engines (note that locomotives are also excluded.) Non-road engines are a far more diverse group of products engines as they include greater than 10,000 kW marine engines as well as 2 kW generators. For a detailed classification of non-road diesel engines the reader is referred to [12].

The last, and least discussed, category of emission standards for diesel engines is based on occupational health and safety standards and is largely related to operation of diesel engines in enclosed spaces such as factories and mines. Understandably, these regulations are typically the strictest. In many cases such standards require the use of diesel particulate filters and very frequent maintenance of the engines. However, the market for such devices is small, and hence the interest from fuel cell developers for these markets has been limited.

The rest of this chapter will discuss the main regulatory markets for diesel engines in more detail.

On-Road Diesel Engines

On-road diesel engines are the most heavily regulated category of engines, primarily because of their dominance in diesel fuel use (Figure 2-1.) Figure 2-1 shows total US distillate fuel oil use for 2001, which includes diesel as well as # 2 Fuel Oil (similar to diesel, accounts for all residential, commercial, and most of industrial uses.) Because this data excludes residual oil, all other categories of use are used primarily in diesel engines. Number 2 fuel oil is not, and will likely not be subject to the same fuel standards discussed here for diesel, and will likely continue to contain significantly higher levels of sulfur and aromatics than diesel.

In the U.S., by far most of the on-road consumption of diesel fuel is in heavy duty vehicles such as trucks and buses, because of the relative unpopularity of diesel passenger cars and light trucks. In Europe, with a much higher proportion of passenger cars fueled with diesel, passenger car and truck consumption are roughly equal.

Heavy Duty

Heavy duty diesel engine regulations for the U.S. and Europe will be substantially tightened by 2010 and largely harmonized across geographic regions. Heavy duty engines are used in a wide range of vehicles, ranging from heavy pick-up and delivery trucks to Class 8 long-haul trucks and buses. Engine capacities range from around 150 kW to around 500 kW, and many engines are highly sophisticated turbo-charged engines. Duty cycles vary dramatically, including significant idling time.

The diesel engine is well-matched to the duty cycle and other design requirements for most heavy duty applications. In addition, its peak efficiency can easily reach the mid-forty percent range and, with appropriate gearing, trucks manage to take full advantage of this high efficiency. Thus few consider primary heavy duty propulsion as an attractive early market for SOFC, except perhaps in transit buses.

Heavy Duty Emissions Standards

Figure 2-6 provides a good overview of the evolution of diesel engine emissions standards for heavy duty on-road diesel engines until 2010. The figure shows that compared with 2000 standards, the US 2007 / Euro 5 standards will require a drastic reduction of both PM and NOx emissions [6, 8, 10, 11]. While it has been demonstrated that achieving US 2002 and Euro 4 standards can be achieved with EGR and a particulate filter (in the case of Euro 4 only), achieving the US 2007 / Euro 5 standards will require aftertreatment for both PM and NOx.

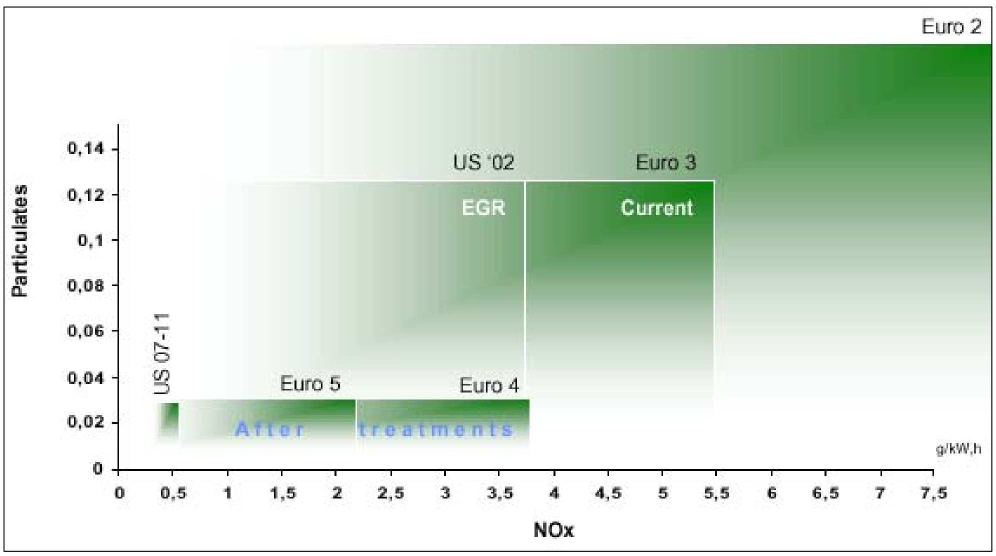


Figure 2-6 Trends in Heavy Duty Diesel Engine Emissions Standards Until 2010 (Source, Volvo Annual Report 2001 [11])

The useful life of heavy duty engines is considered to be between 110,000 and 435,000 miles, after which a major engine rebuild is required. In the U.S., manufacturers must provide an emissions warranty for 100,000 miles during which the standards shown in Figure 2-6 are met, which they must demonstrate to the EPA. In Europe, periodic emissions tests are required.

Heavy Duty Emissions Control Technology

To meet US 2007 and Euro V standards, diesel engines will need to employ still undeveloped emissions control technologies. The emissions reductions required by the US 2007 / Euro 5 standards far exceed the capabilities of current diesel engines and commonly used emission control technologies, and will require new technologies to be employed (Figure 2-7.)

To achieve the almost 90% required reduction in PM emissions, a particulate filter will be required [10] [9]. Disposable particulate filters have been in use in specialized applications such as in mines, but that approach is impractical for on-road applications. Now regenerable particulate filters are being introduced in Europe to comply with Euro 4 standards. Such filters operate in a regenerative mode: after the filter has captured particulate for some time, the organic particulate matter is burned off in a regeneration cycle (in some cases regeneration is done continuously.)

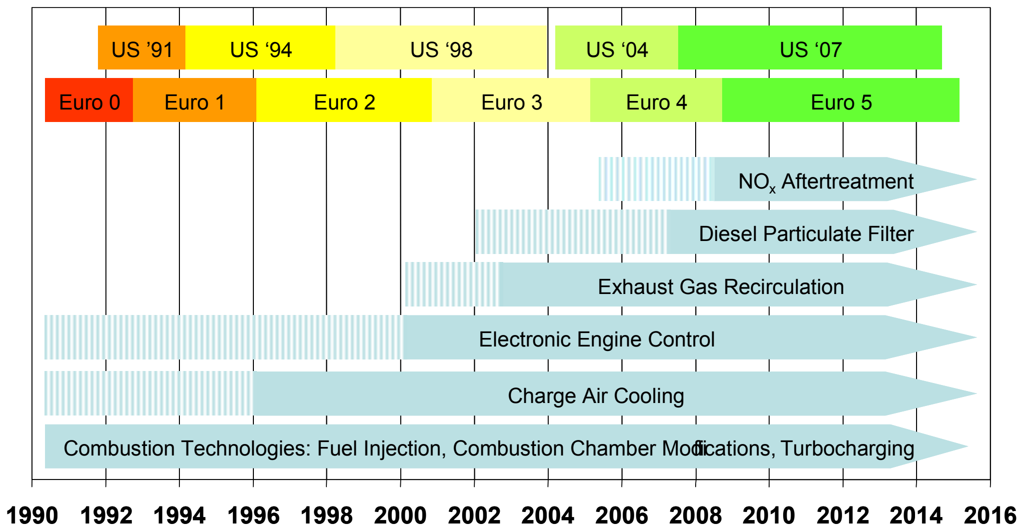


Figure 2-7 Evolution of Heavy Duty Diesel Emissions Control Technology (after: [10])

These filters have shown to be effective although several challenges remain:

- Optimization of the regeneration cycles / process and life of filter;
- Ash management
- Fuel efficiency penalty

More challenging appears to be the development of a practical NOx reduction technology that will meet the US 2007 / Euro 5 requirements. Unlike gasoline engines, which can be operated under slightly fuel-rich conditions to allow catalytic reduction in the emissions control system, diesel engines are operated in a highly fuel lean regime, thus providing no reducing agents in the exhaust stream which can be used to reduce NOx. Thus, to achieve NOx reduction a reducing agent must be introduced. The three basic approaches under development now are:

- NOx Storage Reduction (NSR) Catalyst (NOx absorber) - In NSR systems NOx is absorbed on a storage catalyst, from which it is periodically desorbed under reducing conditions (typically created by injecting additional fuel just before the NSR catalyst), and reduced over a catalyst. NSR systems have been demonstrated to be effective at 80-90% NOx reductions and could meet 2007 US standards.

Also, because the system does not require any additional consumables, it is transparent to the operator. To date however, life of the catalysts has been unacceptable, especially with fuels that contain any sulfur (even a few ppm of sulfur leads to rapid catalyst degradation.) In addition, the cost (about $2,000 to $5,000 per engine), weight (several hundred kg) of the system, and impact on the fuel economy are of concern.

- Selective Catalytic Reduction (SCR) – With SCR systems, a special reducing agent (mostly urea) is injected into the diesel exhaust which is combined with the NOx over a catalyst to form molecular nitrogen and a mixture of CO2 and water vapor. The system effectively reduces NOx and long life has been demonstrated with numerous demonstration vehicles. However the system is not transparent to the operator (who has to tank urea in addition to fuel), leading to a variety of reliability concerns, including establishing a urea infrastructure. Although the cost of urea is of concern, engines with SCR will have better fuel economy than current engines (similar to 1999 vintage engines) which off-sets that cost.

- Ultra-high EGR -- In these systems the EGR rates are increased to achieve the NOx target. This approach has been proven to work, but results in an engine de-rating and a decrease in efficiency.

Table 2-5 Overview of Impact of SCR, EGR, and NSR on Engines and Vehicles (after: [10])

	SCR	EGR	NSR
Fuel Economy	+6% (with ~ 6% urea usage)	-3%	-3%
Cooling requirements	-20%	Up to 55%	0
Power density	+6%	-5%	
Weight	-400 lbs	+50 lbs	+200 lbs
Oil exchange intervals	2x	1x	1x
Urea infrastructure required	Yes	No	No
Driver's responsibility	Urea refill	None	None

Both the SCR and EGR technologies are considered seriously, with Europeans apparently leaning towards SCR and the U.S. market possibly moving towards EGR, based on recent announcements.

As Figure 2-7 indicates, in addition to these aftertreatment technologies a further sophistication of engine combustion and management technologies will be required. Overall, these modifications will have impacts on a variety of aspects of engine and vehicle design and operation.

Idling Emissions

Idling emissions of Heavy Duty trucks and buses are starting to receive considerable regulatory attention, making Heavy Duty vehicles potentially good candidates for APUs, including SOFC-based APUs. Trucks idle to heat and cool the cab and sleeper, provide electrical power, keep the fuel warm in winter, avoid cold starting, and for personal safety. Long-haul trucks typically idle 6 hours per day, or 2,400 hours per year, but actual practice varies, from idling 1-2 nights per week to hardly ever turning the engine off [23] [24].

The environmental and energy use impact of engine idling is disproportionally large compared with the amount of useful power that is generated. Idling truck and bus engines often operate at less than 1% of rate power. At such a low output level the engine efficiency is less than 10%. In addition, the engine emissions have high emissions. CARB estimates that during idling of heavy duty engines NO_x emissions are 81 grams per hour and PM emissions are 1 gram per hour [24]. Given a engine useful power output of around 1 kW, this would result in emissions around two orders of magnitude higher than those during normal engine operation for the US 2007 / Euro 5 standards, and one order of magnitude worse than those during normal operation for current engines. Finally truckers dislike the noise of the idling main diesel engine during the night.

By 2010, it appears likely that at least some jurisdictions, such as California, will be regulating idling of heavy duty vehicles. Although almost all states and municipalities have some form of regulations that could address truck idling as a nuisance, these regulations are rarely enforced (except in Boston and New York City.) In addition, the duty cycles used in emissions standard testing in the U.S. and Europe do not include significant idling time, and thus the idling emissions of such vehicles are not being addressed by current regulations. To address this source of emissions, CARB has proposed idling restriction regulations which would limit idling of heavy duty diesel vehicles (greater than 14,000 lbs GRVW) to 5 minutes. Vehicles would have to use alternative technologies to provide the necessary power, heat, or cooling.

These trends are driving the development of numerous APU systems, stand-alone cab-heaters and air-conditioners, and truckstop electrification systems. EPA's web-site provides a useful summary of the commercially available products. The cost of the current APU systems (SOFC APUs main competition) is around $6,000 to $7,000 for a 3.5kW to 8 kW single or double cylinder diesel-based APU (exclusive of installation which adds another $2,000 per vehicle.)

Light Duty

Light duty diesel vehicle emissions standards in the U.S. and Europe will also be substantially tightened by 2010. The U.S. standards will be strictest, and match the standards for light duty gasoline vehicles, while European standards will be somewhat less stringent with respect to NOx and PM. Light duty standards are for the vehicles, rather than the engines separately (both in the U.S. and Europe.) An overview of the standards is provided in Table 2-6 below.

Table 2-6 Overview of 2010 light duty vehicle emission standards for diesel vehicles [5, 6]

Cars & Light Trucks Region	Regulations Designation	Timeframe	Nox g/km	PM g/km	CO g/km
US Federal Tier 2	bin 8	2004	0.13	0.01	2.63
	bin 7	2004	0.09	0.01	2.63
	bin 6	2004	0.06	0.01	2.63
	bin 5	2004	0.04	0.01	2.63
	bin 4	2004	0.03	0.01	1.31
	bin 3	2004	0.02	0.01	1.31
	bin 2	2004	0.01	0.01	1.31
	bin 1	2004	-	-	-
CARB LEV II (passenger cars < 8,500 lbs GVWR)	LEV	2004	0.04	0.01	2.63
	ULEV	2004	0.04	0.01	1.31
	SULEV	2004	0.01	0.01	0.63
CARB LEV II (Medium Duty 8,500 -10,000 lbs GVWR)	LEV	2004	0.13	0.08	4.00
	ULEV	2004	0.13	0.04	4.00
	SULEV	2004	0.06	0.04	2.00
CARB LEV II (Medium Duty 10,000 -14,000 lbs GVWR)	LEV	2004	0.25	0.08	4.56
	ULEV	2004	0.25	0.04	4.56
	SULEV	2004	0.13	0.04	2.31
Euro 4	Passenger	2005	0.25	0.03	0.50
	LC <1305 kg	2005	0.25	0.03	0.50
	LC 1305 - 1760 kg	2005	0.33	0.04	0.63
	LC >1760 kg	2005	0.39	0.06	0.74

To achieve these standards, engine developers face the same challenges as those they face for heavy duty vehicles. Many expect however that the use of urea for light duty vehicles will compromise convenience too much to be widely accepted by drivers, and thus NSR is likely to be the only solution for NOx reduction, though it is yet to be developed.

Non-Road Diesel Engines

While non-road diesel engines come in an extremely wide variety of capacity and are used in a similarly wide range of applications, the emission standards that apply to them can fall into three categories: marine, locomotive, and others. The latter category is critical for this report as it contains many of the early SOFC target markets. In addition, many of the diesel engines that are used as APUs and with which SOFC might compete in early markets, are regulated under this category.

Other Non-Road Diesel

The other non-road diesel category covers a wide range of diesel applications, including:

- Small marine engines and sailboat auxiliaries (marine engines greater than 50 hp are regulated separately in U.S.)
- Locomotives (regulated separately in the U.S.)
- Portable engines such as small generators and those used in lawn and garden equipment (few of the latter are diesels)
- Construction equipment
- Farm and logging equipment
- Industrial vehicles (e.g. forklifts)
- Small generators and stationary engines

Though most of the engines in this category are relatively small (3 to 37 kW), construction equipment, industrial vehicles, and farm and logging equipment can have engines with capacities up to 500 kW. As can be expected, the smallest engines typically use rather simple diesel technology, while the larger engines can use quite sophisticated technology, though regulations do not (yet) force them to be as sophisticated as those used in heavy duty vehicles. For a more extensive review of the types of applications categorized as non-road diesel engines, please refer to [12].

Other Non-Road Emission Standards

By 2010, emission standards for other non-road diesels will be considerably tightened and for the larger engines will match those that apply to on-road diesels. Because non-road diesel engines are categorized by engine capacity, and because introduction of new standards occur at different times for different engine size classes in each regulatory market, we first provide an overview of the applicable standards (Figure 2-8). Figure 2-8 also emphasizes that these engine classes will face an almost continuous drive for lower emissions between now and 2014.

Non-Road Diesel Engine Emissions' Standards

	Engine Ca	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
US	<8kW	Tier 1		Tier 2			Tier 4*					
	8-19	Tier 1		Tier 2			Tier 4*					
	19-37	Tier 1	Tier 2									Tier 4*
	37-56	Tier 1	Tier 2				Tier 3					Tier 4*
	56-75	Tier 1	Tier 2				Tier 3				Tier 4*	
	75-130	Tier 2				Tier 3					Tier 4*	
	130-225	Tier 2			Tier 3					Tier 4*		
	225-450				Tier 3					Tier 4*		
	450-560				Tier 3					Tier 4*		
	>560				Tier 2		Tier 3			Tier 4*		
EU	<19											
	18-37	Stage II		Stage III								
	37-75	Stage I	Stage II			Stage III				Stage IV*		
	75-130	Stage II			Stage III				Stage IV*			
	130-560	Stage II		Stage III					Stage IV*			

* these standards are proposed but not yet adopted

Figure 2-8 Overview of Applicable Emissions Standards for Non-Road Diesel Engines [12] [8]

Emission standards for other non-road diesel engines are currently much less stringent than those for on-road diesel engines. But starting in 2005, both the U.S. and the EU have adopted standards (US Federal Tier 3 regulations and EU stage III) that would bring diesel emissions from non-road diesels closer to on-road standards (Figure 2-9, Figure 2-10) [8, 12]. In addition, both the EPA and the EU Commission

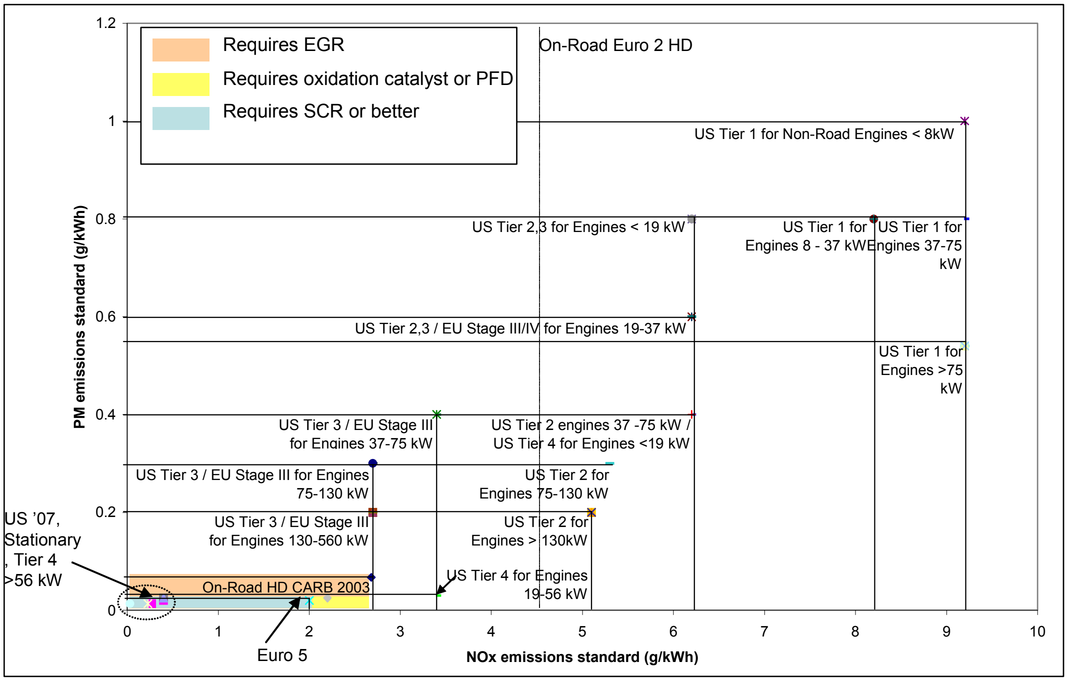


Figure 2-9 Overview of Diesel Emissions Standards, High Range [8, 12] [6]

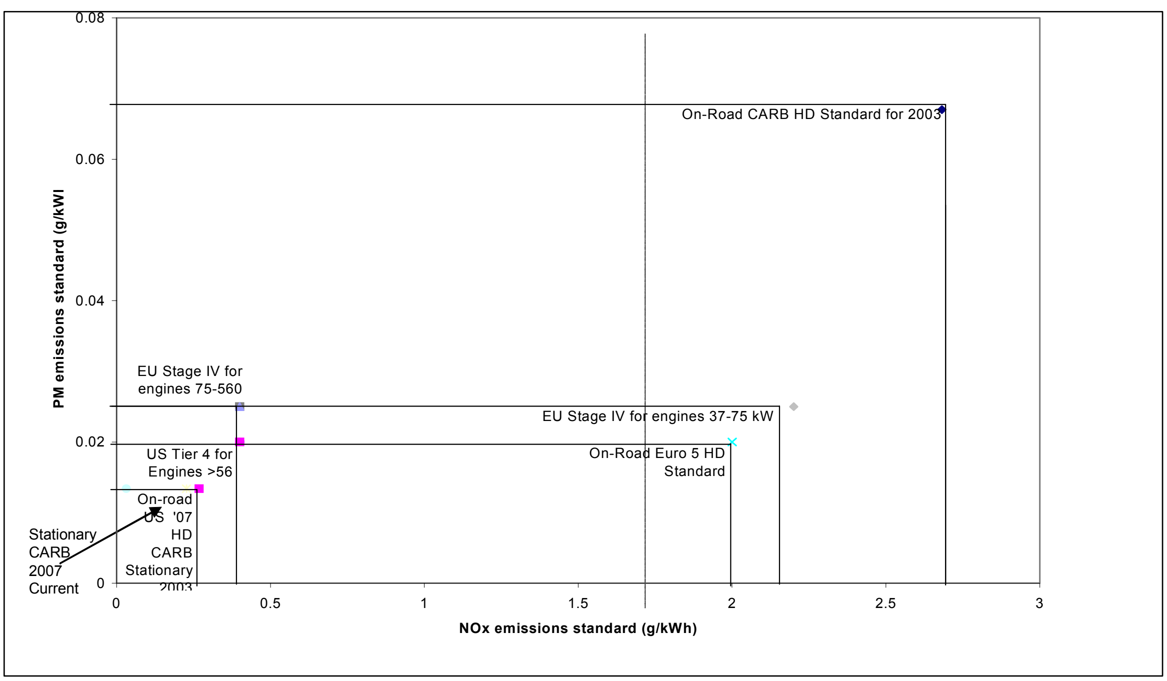


Figure 2-10 Overview of Diesel Emissions Standards, Low Range [6, 8, 12]

have proposed very similar standards to be phased in between 2008 and 2014 that would bring the largest non-road engines on par with on-road engines, and also brings consistency and more stringent requirements to the lower capacity engines. In the U.S. these regulations will also extend to the smallest diesels (below 19 kW) which may be the primary competing technology for early diesel-fueled SOFC applications such as APUs. Both standards would require the use of 350 ppm (for Europe) and 500 ppm (for the U.S.) diesel fuel, and of 15 / 10 ppm diesel eventually.

In the past year, both the US EPA and the European Parliament have proposed even stricter standards which would essentially hold non-road engines larger than 18 kW (25 hp) up to the same standards as on-road engines by 2010 (US Federal Tier 4 and EU Stage IIIb.) These proposed standards are currently in the public review process.

Compliance with the Tier 3 / Stage 3 regulations will likely require the use of advanced engine controls as well as EGR and possibly oxidation catalysts. While this may be relatively simple for the medium to large engines (larger than 37 kW) by adopting on-road diesel technology, for smaller diesel engines such technology transfer may be less straightforward and it will almost certainly have a much more significant impact on cost on a kilowatt basis. EPA claims that the cost of compliance will be in the 1% to 2% range. However, it provides an example of a $250,000 bulldozer to substantiate the claim, leaving one to wonder whether a 1% to 2% increase is equally realistic for a $7,000 diesel APU.

Marine

In the U.S., marine diesel emissions will be regulated to standards similar to the 2000 standards for on-road diesel. In the U.S., larger (greater than 37 kW or 50 hp) marine diesel engines are regulated separately. Smaller marine diesel engines (up to 1,000 kW), of most interest here, operate mostly on 2DF. Larger diesels operate on number 4 diesel fuel (4DF), while large 2-stroke diesels operate on residual fuel oil (number 6 or bunker C). While eventually SOFC may compete with diesels that use these heavier oils, early products will likely not and this report will focus on the applications where 2DF is used.

Between 2004 and 2007 federal Tier 2 standards will be phased in which will regulate emissions to:

- NOx + THC < 7.2 – 11.0 g/kWh (7.2 – 7.5 for recreational vessels)
- PM < 0.2 – 0.5 g/kWh (0.2 – 0.4 for recreational vessels)

In Europe, standards for marine engines will be the same as those for other non-road engines.

Locomotive

In the US, locomotive diesel engines will have to meet Federal Tier 2 regulations by 2005:

- NOx < 5.5 g/bhphr (< 8.1 g/bhphr for switch service)
- PM < 0.2 g/bhphr (< 0.24 g/bhphr for switch service).

In Europe, standards for locomotive engines will be the same as those for other non-road engines.

Locomotives are another prime potential application for APUs, as trains also idle a very large portion of the time (as much as 75% of the time.) Train engines are often kept on 100% of the time, and the rail yards and stations where idling is done are often in urban areas. Thus EPA considers locomotives as the second potential application for APUs.

Stationary Diesel

Stationary diesel engines are regulated as stationary sources, and thus regulated through a different mechanism than all the other diesel engines discussed here. Stationary diesels typically range in capacity from a few kW (mostly for back-up power or direct-drive pumps) to thousands of kW conventional stationary power generation. While in many areas such engines may be operated on natural gas, in other applications they are operated on distillate fuel.

As stationary sources stationary diesels that perform normal power generation or co-generation service (i.e. not back-up power) are subject to Best Available Control Technology, prevention of non-significant deterioration, or other standards. As a result, depending mainly on the location and application, stationary diesel standards could be substantially more relaxed than those for on-road diesels (e.g. power generation in rural areas), but in many cases will require equally low emissions as on-road diesels. This is especially true as regulators recognize that diesel emissions, even with the most advanced emissions controls, are still high compared to those from other power generation technologies such as gas turbines.

Despite the absence of federal regulations on stationary diesel engines, several states have promulgated regulations specific to distributed generation (DG) sources in which many of the stationary fuel cell installations would likely fall. The leading states in this respect are California and Texas. Current standards reflect the available technology for DG: mostly engines with capacities less than 100 kW and micro-turbines with capacities less than 300 kW, according to CARB. In 2007, a more stringent standard will come into effect, which is based on the federally established Best Available Control Technology standard for central power generation stations. An overview of these regulations is provided in Table 2-7 below. Currently, two micro-turbines and two fuel cells have been certified. The micro-turbines have been certified to 2003 standards and the fuel cells to 2007 standards. These regulations have the effect of outlawing diesel generators for DG. After 2007 it is likely that only fuel cells and micro-turbines with advanced catalytic burners will be certifiable; engines are unlikely to be able to achieve these emission levels.

Table 2-7 Emissions standards applicable to DG technologies [1-3]

Stationary DG			NOx g/kWh	PM g/kWh	CO g/kWh	Nox lb/MWhr	PM lb/MWhr	CO lb/MWhr
California	w/o cogen	2003	0.227		2.724	0.5	*	6
	w/ cogen	2003	0.3178		2.724	0.7	*	6
	all	2007	0.03178		0.0454	0.07	*	0.1

* limited to sulfate emissions from CARB-spec natural gas

Diesel fuel applications in stationary power generation however are mostly limited to remote areas, where natural gas is unavailable.

3 Impact of Diesel Fuel Quality on SOFC Performance and Cost

Impact of New Fuel Specifications on SOFC Performance and Cost

Background

Although the sensitivity of solid oxide fuel cells (and other fuel cells) to fuel contaminants such as sulfur is much mentioned, relatively little experimental data (quantitative or qualitative) on the effects has been reported. As diesel fuel specifications change and reduce the levels of sulfur and aromatics in diesel fuel, the task of developing fuel cells that are compatible with such fuels undoubtedly becomes easier. The following summarizes the current state of the art as reported in the literature, and some limited analysis to estimate the impact of the changes.

Impact of Diesel Fuel Sulfur

Impact on Stack

Experimental Data

The few studies that have discussed the impact of sulfur on the fuel cell stack have shown that SOFC stacks are severely poisoned by sulfur at concentrations of 1 ppm or less [14, 15], when operating at high SOFC operating temperatures (~1000 °C.) Figure 3-1 summarizes the latest results reported by Tokyo Gas [16], in which temperatures as well as the concentrations and partial pressures of sulfur were varied while the anode performance was monitored using complex impedance spectrography. The data dramatically shows that at lower operating temperatures, the limited sulfur tolerance of the Ni-YSZ anodes is further compromised considerably. At 750 °C, similar to the operating temperature targets of several of the SECA participants, even concentrations of 50 ppb were found to poison the anode severely.

These results are consistent with earlier results in which Singhal and others found that when operating at 1273 K SOFC with conventional Ni-YSZ are sulfur tolerant up to 1 ppm [14, 15].

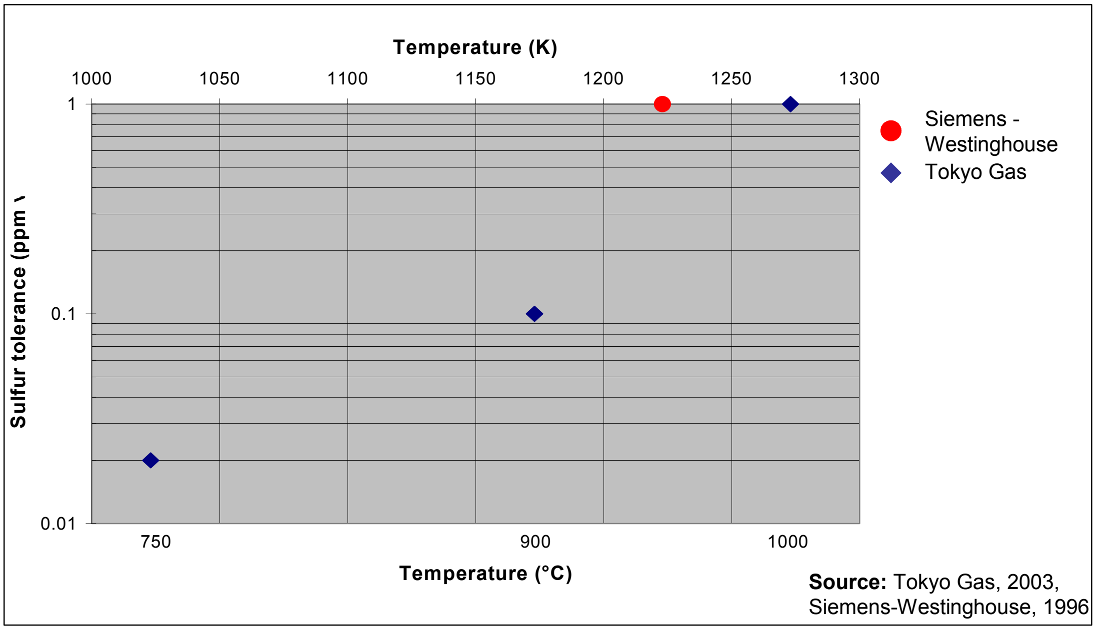


Figure 3-1 Sulfur Tolerance of Ni-YSZ-Based Anodes (Source: Matsuzaki et al. [16])

Another point of agreement between the various studies is that all found sulfur poisoning to be reversible at low sulfur concentrations. When operating at 1000 °C, all found that anodes poisoned in a gas with sulfur content of ~15 ppm recover fully within one hour. However, at 750 °C the recovery time stretches to more than a day. In addition, some research has shown that poisoning with gases with higher sulfur content of 105 ppm resulted in a doubling of the overpotential and that the poisoning was not reversible. We must consider that such experiments have only run for a few dozens of hours, and it is not clear whether the behavior with respect to tolerance levels or with respect to reversibility will be the same for the thousands of hours required for economically viable stack life.

To date, all the publicly reported experimental data is based on tests in which H_2S is added as the sulfur species. However, in the case of future diesel fuels, some (indeed possibly a large fraction) of the sulfur that will enter the anode will be in organically bound form.

Sulfur-Tolerant Anodes

In recent years, several efforts have been under way to develop sulfur-tolerant SOFC anodes. Some promising results have been reported showing resistance to the effects of sulfur up to concentrations of 100 ppm. However, the electrochemical performance of these anodes was inferior to that of Ni-YSZ anodes, making further improvement necessary. In addition, ceramic anodes are not generally expected to exhibit water gas shift activity necessary for effective CO utilization within the SOFC stack. Such capabilities must be added.

Relationship Between Sulfur Levels in Fuel and in Anode Feed Gas

The sulfur tolerance of anodes is typically (as in the examples above) reported in ppm volume in the gas-phase anode feed. This may be confusing as fuel concentrations are also reported in ppm mass. However, given a reforming approach, and absent any sulfur removal (this may not be possible in reality), the concentration in the anode feed can be related linearly to the fuel sulfur concentration, as is shown in Figure 3-2.

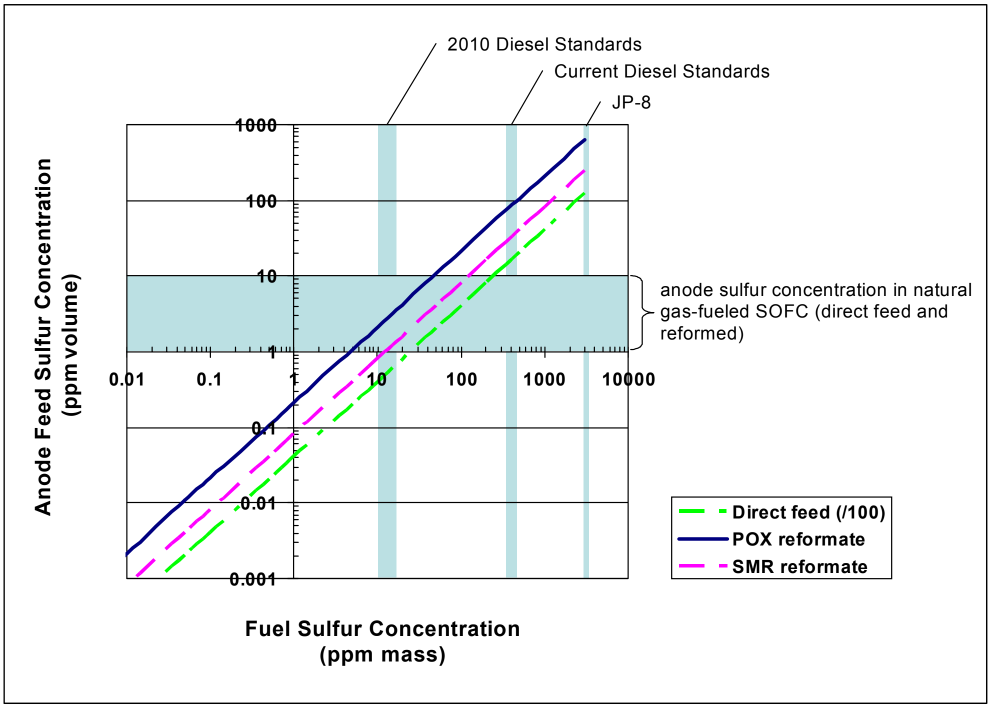


Figure 3-2 Relationship Between Fuel and Gas-Phase Concentrations of Sulfur in SOFC (Note: Direct feed curve represents 1/100 of concentration)

To be able to avoid sulfur removal from an SOFC with a sulfur tolerance of 1 ppm (like the 1223 K example in Figure 3-1) the fuel sulfur concentration must be below 10 ppm. It is also plain that unless the fuel is completely sulfur-free, a fuel cell with a sulfur-tolerance of 20 ppb will require desulfurization. It is also noteworthy that with the ULSD standard the anode feed concentrations will be similar to those found in SOFC fueled with odorized natural gas.

Research, Development and Design Impacts

While with conventional anodes it appears obvious that some desulfurization or sulfur polishing will be required, the amounts of sulfur removed will be so small that in most applications a sulfur removal cartridge properly sized to achieve the desired level of removal will live longer than the stack, thus reducing the maintenance burden on the user.

Developers of sulfur-tolerant anodes can also deduce appropriate sulfur tolerance R&D targets from Figure 3-2. If targeting markets where ULSD or odorized natural gas are used, an anode that is tolerant of sulfur concentrations of 10 ppm is sufficient, unless direct oxidation is used (then the tolerance level required is around 60 ppm.) If conventional diesel is used, a 100 ppm target would be reasonable, and with JP-8 the required level would be around 650 ppm and as high as 12,000 ppm in the case of direct oxidation.

Impact on Balance of Plant

The impact of sulfur on the balance of plant falls into two categories: the impact on the design and operation of the reformer, and the impact on the design and operation of the sulfur removal system.

Impact on Reformer

The sulfur tolerance of the reformer depends strongly on the type of reformer that is being used. Four main types of reformers are typically considered:

- Gas-phase partial oxidation (POx) reformers, such as the one in the conceptual design in the Arthur D. Little report cited earlier, are not affected by level of sulfur in the fuel. POx reformers typically convert all organically bound sulfur to H_2S and COS provided POx temperatures are kept above 900 °C.
- Short contact time catalytic partial oxidation (CPOx) reformers such as those pioneered by the University of Minnesota, Shell, and ConocoPhillips, may have some unique benefits in operation with diesel fuel (see aromatics section.) These reformers have been demonstrated to have tolerance to sulfur-containing feeds up to 100 ppm with special catalysts (ruthenium- or rhodium-based.) Such reformers have been extensively tested in fuel cell systems. If CPOx operate at temperatures above 850 to 900 °C most organically bound sulfur is converted to H_2S and COS.
- The oxidation zone of conventional autothermal reformers (ATRs) typically provides sufficient sulfur tolerance to handle conventional U.S. gasoline and diesel fuels. The steam reforming zone however is sometimes more prone to sulfur poisoning. When conventional Ni-based steam reforming catalysts are used (as in large-scale ATRs in refineries), operation with ULSD is feasible but operation with conventional diesel fuel or JP-8 would require sulfur tolerant ATR catalysts or desulfurization prior to the reformer. Sulfur tolerant catalysts are now under development and have been tested in fuel cell systems. If ATRs operate at temperatures above 850 to 900 °C most organically bound sulfur is converted to H_2S and COS.
- Steam reformers (SRs) are most susceptible to sulfur poisoning. Conventional Ni-based reforming catalysts are as susceptible to sulfur poisoning as Ni-based anodes. The rule-of-thumb from industry is that sulfur levels must be kept below 50 ppb. Thus conventional steam reformers are poisoned by either conventional

or ULSD fuel. A number of sulfur-tolerant steam reforming catalyst developments are under way, mainly ruthenium- or rhodium-based and using a support that incorporates high O-solubility (e.g. CeO2.) Such reformers have been shown to operate with feeds with higher sulfur levels, which would seem to allow them to operate on ULSD, but operation with conventional diesel or JP-8 remain doubtful. The sulfur speciation in the products of such reformers is currently unknown.

Impact on Sulfur Removal System

Unless successful sulfur-tolerance SOFC anodes are developed, the main impact of the change in sulfur specifications in the diesel fuel will likely be on the design and operation of the sulfur removal system. To understand the impact, we first review the most commonly proposed sulfur removal technologies. Because organically-bound sulfur is difficult to remove, most developers propose to remove sulfur between the reformer and the fuel cell, where organo-sulfur will hopefully be broken up into H_2S, COS, and hydrocarbons. It is still not clear whether sorbent-based systems that work on the fuel can achieve the level of removal required for conventional SOFC anodes. Once the sulfur is in the form of H_2S or COS, it can be removed by a variety of metal/metal-oxide based sorbents, the most popular of which is ZnO. The H_2S reacts with the ZnO in an equilibrated reaction to yield ZnS and H_2O. Because the reaction is in equilibrium, both temperature and the relative partial pressures of H_2S and H_2O determine the level of removal achievable. In the Arthur D. Little study the system was operated at 400 °C to yield a H_2S concentration of 300 ppb. To achieve removal down to 20 ppb a lower operating temperature would be required. The operating temperature is determined by the stack sulfur tolerance and reformate water partial pressure only, and is not affected by the fuel sulfur content.

Another factor in the design of the desulfurization system is the size of the system. The bed needs a certain size to ensure that no break-through occurs under any of the operating conditions, considering kinetics and safety factors. In addition, sufficient sorbent material must be incorporated to store the sulfur for the life of the bed. This quantity naturally depends on the required sulfur removal rate. Thus when the sulfur content of the fuel is drastically reduced, the sulfur removal rate drops more than proportionally. Hence it can be expected that for most SOFC systems that operate on diesel, a sulfur bed that was designed to last for several thousand hours based on 500 ppm fuel, can now last for the life of the system. Though it may not allow shrinking the sulfur removal system very much, it could well eliminate any maintenance required for the sulfur removal system. Effectively the system has become a sulfur polishing system, rather than a sulfur removal system.

Impact of Aromatics Content

The expected reduction in carbon content in the fuel (reduction by one tenth to one half of current carbon content) will likely have a noticeable but not dramatic impact on SOFC system operation:

- Carbon formation will remain an issue with use of diesel fuel;
- The range of operating conditions under which carbon formation can be avoided can be somewhat extended;
- Where carbon formation cannot be avoided, the deposition rate will be reduced roughly proportionally to relative reductions in aromatics and PAH content, thus requiring less maintenance for the fuel cell system.

Experimental data on the effect of the aromatics content (or for that matter any other aspect of hydrocarbon structure) on fuel cell system operation is scarce. Recent reports from Delphi suggest that operation of their POx reformer on Swedish specification diesel was successful. However, only short-term test data were provided. Similarly, Idatech and Nuvera reported a few years ago that their fuel processors (for PEM fuel cells) performed better when operated on GTL diesel and JP-8 than on conventional gasoline or diesel (GTL diesel has no aromatics.) However, 2010 specification ULSD will have aromatics and PAH content more comparable with that of current conventional diesel than with GTL diesel.

Theoretically, aromatics and PAH are more prone to carbon formation than other hydrocarbons for two principal reasons:

- Their hydrogen to carbon ratio is lower; hence they are thermodynamically more prone to carbon formation (Figure 3-3.) This tendency becomes more pronounced at lower temperatures.
- The kinetics of carbon formation from aromatics is much faster than for other species, primarily because their chemical structure closely resembles that of solid carbon already. The kinetics of these reactions depend strongly on the catalyst and operating environment, and in many cases kinetic pathways allow carbon formation inside fuel cell systems even though it is not favored overall according to thermodynamics.

Thus, the thermodynamics alone are not enough to understand whether carbon will form in a given situation. Figure 3-3 shows the range of impact that may be expected from a change in composition going from conventional diesel to GTL diesel. Such and extreme change reduces the carbon formation limit by as much as 100 °C, allowing operation at lower temperature or reduce the required fuel equivalence ratio (phi) for POx reformers and the S/C for steam reformers by around 0.1 to 0.2 (e.g. from 3.0 to 3.15). This would result in an improvement in reformer efficiency of a few percent, and perhaps a 1% improvement in overall system efficiency. In the less extreme case of ULSD the impact would be less than that.

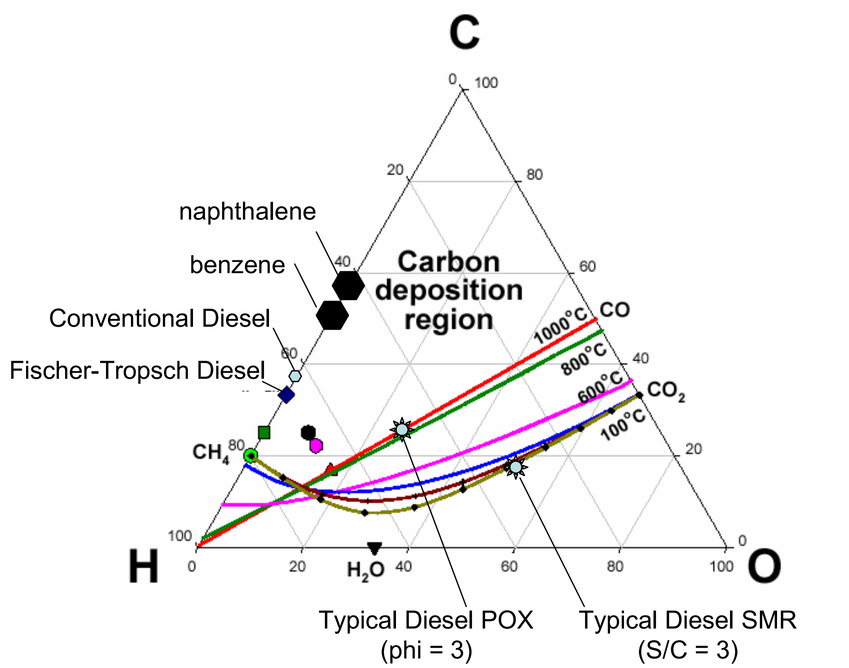


Figure 3-3 Equilibrium Carbon Formation Region Relevant for SOFC

The impact of the reduction in aromatics and PAH resulting from the new fuel specifications via changes in kinetic mechanisms could be more substantial but, given the modest changes in aromatics content expected, this impact too is likely to be limited. Without more detailed analysis of the changes in fuel composition, experimental data, and detailed kinetic analysis, we cannot determine the likely impact quantitatively.

System Impact and Cost Implications

To assess the potential overall impact of changing diesel fuel regulations on SOFC systems and on their manufactured cost, we revisit a study performed by Arthur D. Little in 2001 [17], in which they studied and compared a POx-based SOFC APU operated on sulfur-containing gasoline with one fueled with FT-diesel (with zero sulfur and aromatics.)

The analysis indicates the simplifications that can be made in the base case system (Figure 3-4) design if no desulphurization is needed:

- Sulfur trap can be eliminated

- Heat exchanger sizes can be reduced: the desulfurization beds must be operated at temperatures in the range from 250 to 400 °C in order to achieve the level of desulfurization required. In the sulfur-free case the exhaust from the reformer does not need to be cooled down (as much) and does not need to be reheated prior to entering the anode of the fuel cell.

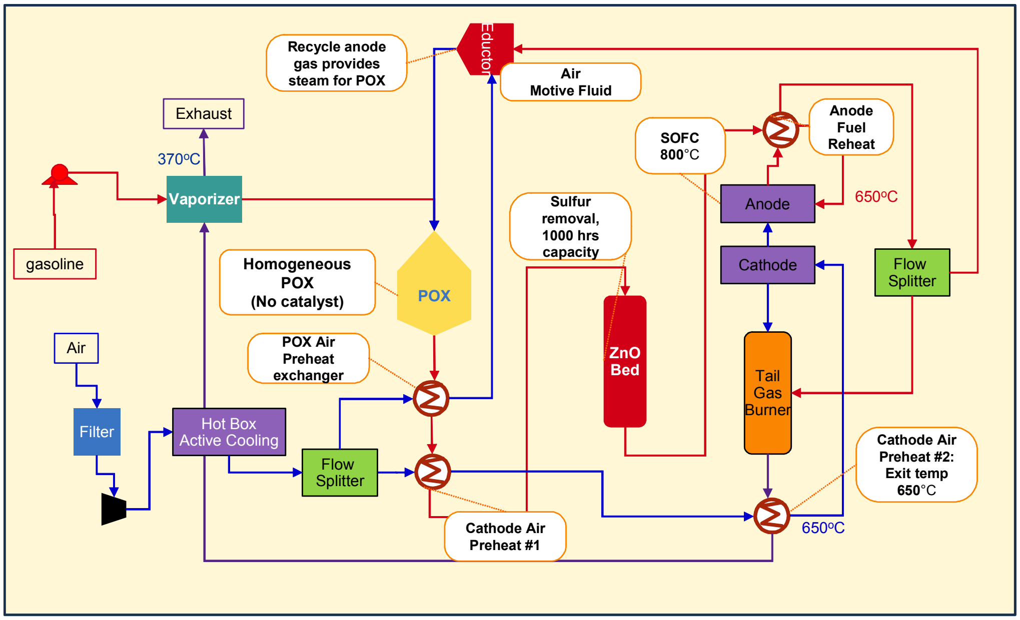


Figure 3-4 Example of Small SOFC System Design for Sulfur-Containing Fuel (source: [17])

Otherwise changes in the design are minor. The impact of the fact that the sulfur-containing fuel was a gasoline-grade fuel and the sulfur-free one a diesel-grade fuel is thought to have negligible impact on the results, other than that no provisions were made to deal with the diesel as a heavier fuel, because a FT-diesel contains no aromatics. The study estimated that these changes would reduce component volume by about 5% (system volume by about 2%) and system cost by about 8% (Table 3-1.)

Compared with the cases studied, the change from current CARB diesel to U.S. federal 2007 standard ULSD is different in the following ways:

- Current CARB diesel can have an up to ten times higher sulfur content than the gasoline considered in the ADL study. A similar system using CARB diesel would require a reformer catalyst with 500 ppm sulfur tolerance, to our knowledge such a catalyst is not available. The sulfur removal system would have to be resized, resulting in an approximately 10 times larger system (adding 17 liters and about $250 to the cost of the system);
- Typical aromatics content in RFG ranges from 26% - 32% by volume, lower than the 35% found in current U.S. federal specification diesel, but higher than the

level found in CARB diesel (Table 2-3.) This would have no appreciable impact on system design, operation or cost;

- Polyaromatic and polynaphthene content in gasoline is typically much lower than that in diesel. This would likely impact the carbon formation region significantly, and it is doubtful whether it would be possible, with currently available catalyst technology, to develop a system that would operate stably without excessive carbon formation in the reformer or the stack. In this analysis, the assumption was that such a catalyst can be developed and the added cost for it was taken into account.

Table 3-1 Impact of Use of Sulfur-Free Fuel on System Volume and Cost (Source: [17]; Note: in addition to component volume there is about 58 liters in each system for packaging and insulation)

	Base Case (50 ppm Gasoline)		Sulfur-Free (Fischer-Tropsch Diesel)	
	Component Volume (l)	**Cost ($)**	**Component Volume (l)**	**Cost ($)**
Fuel cell stack	14.8	1184	14.8	1189
Reformer	6.8	121	6.8	121
Sulfur-trap	1.7	50	NA	NA
Tailgas burner & cathode heat exchangers	9.4	200	9.4	177
Anode heat exchanger	0.3	62	NA	NA
Rotating Equipment	10.4	381	10.4	381
Balance (controls etc.)	0.5	420	0.5	427
Labor, Indirect	NA	215		167
Total	43.9	2636	41.9	2461

Following the logic of the ADL study, and taking into account the abovementioned differences, a high-level cost comparison was performed to develop a sense of the maximum impact of new diesel fuel on SOFC system cost (Figure 3-5) and efficiency. Considering the analysis was done for a 5 kW system, the analysis shows that a design for operation with CARB diesel would impose an $80 per kW premium on the diesel SOFC compared with the gasoline SOFC. While a similar premium is not uncommon for diesel engines (compared with spark ignition engines), the CARB diesel SOFC will probably require more intensive maintenance than a gasoline SOFC whereas diesel engines provide a reliability and life benefit over spark ignition engines.

The other significant effect is an approximately 10 liter reduction in system volume, resulting from the elimination of the sulfur trap, bringing the volume of the ULSD SOFC back to the same size as that of the gasoline SOFC.

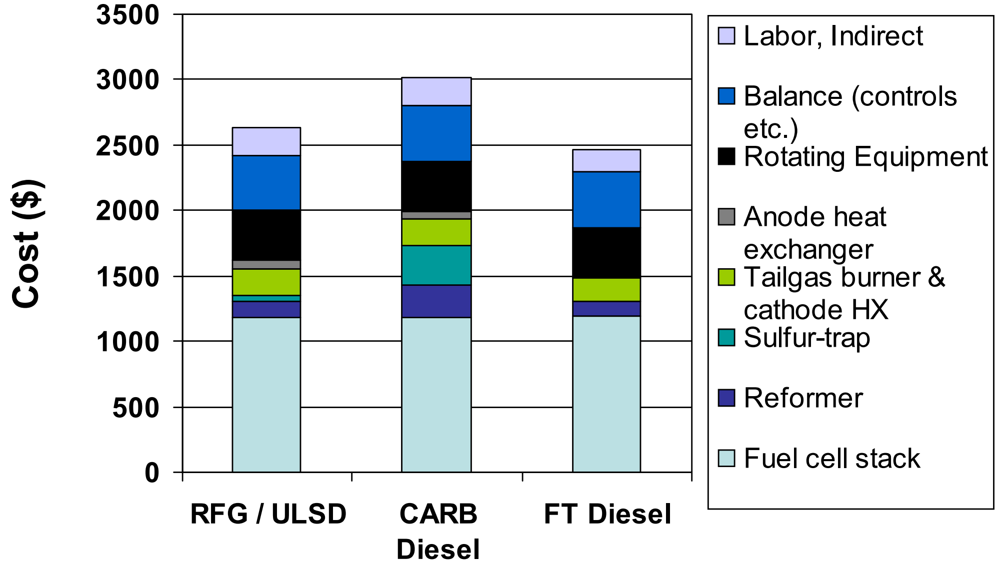


Figure 3-5 Estimated Impact of Change from CARB Diesel to Zero Sulfur, Zero Aromatics Fuel on Manufactured Cost of 5 kW SOFC APU (After [17])

4 Impact of Changing Diesel Regulations on National Benefits of SOFC

Background and Overview

It is important to know how the changes in diesel regulations will affect the national benefits of SOFCs specifically in light of DOE's R&D program. There are two main effects that may result from the changes in diesel regulations:

- Stricter diesel fuel specifications could make it easier to develop competitive diesel-capable SOFC, thus possibly accelerating their development and reducing their cost;
- Lower emissions from diesel engines will reduce the emissions benefits of SOFC, but, at the same time, increase the cost and fuel consumption of compliant diesel engines.

To quantitatively illustrate how these effects will affect the national benefits of SOFC, we made the following considerations:

- Assess the effect of changes in diesel regulations by 2015 (2010 which would be too close to both the introduction of diesel SOFC and to the introduction of the new standards to see meaningful effects);
- Focus on four selected application markets: APUs, remote telecoms and industrial, mobile generators, and small non-road vehicles. Military applications are mostly analogous to their civilian counterparts and will be considered in the analysis of APUs and mobile generators. These four applications are meant to illustrate the impacts, not to capture all, or even most, of the impacts;
- Assess the benefits (energy use, emissions, cost) of SOFC per unit installed for each market application;
- Estimate the market potential for SOFC in each market application;
- Project how the timing of the market introduction of diesel SOFC might change as a consequence of the stricter diesel specs.

The latter consideration is common to all of the markets selected and will be discussed first. The other considerations will then be made per application. Only the potential market impact is analyzed here; not the true level of market penetration or market share of any of the technologies.

Of course, the importance of diesel SOFC in terms of national benefits goes well beyond the five selected target markets (which were selected because they are seen as plausible near-term markets for diesel SOFC):

- Diesel SOFC applications are part of the overall market for SOFC, and sales in diesel markets could increase the overall sales of key SOFC components (referred to by some as mass-customization) thus improving the economics for all SOFC applications. The benefits of other SOFC applications are likely to be orders of magnitude higher than those for the individual small-scale diesel SOFC applications;
- Small diesel SOFC applications may eventually pave the way to more challenging, larger-capacity mobile diesel SOFC applications, such as truck, train, and marine propulsion. Again, the potential impact of these large-volume SOFC applications is likely to be substantially greater than that for the small-scale applications.

As data sources for this work, we used DOE data wherever possible, for maximum consistency with other DOE impact assessments. Where such data was not available, data from other government agencies was used. Specifically, we used information from the EPA's draft impact assessment for the new proposed non-road diesel regulations [12], which covers all the market applications of diesel considered here.

Impact on Diesel SOFC Development Timeline

The new diesel SOFC standards will substantially improve the chances that a competitive diesel SOFC system will be commercially available by 2015. Although forecasting the rate of development and the timing of commercialization of emerging energy technologies is difficult, we can consider the stages each development has to move through and the characteristic minimum time it takes to traverse each stage. Figure 4-1 shows these stages as they apply to the development of energy technologies. Currently, the SECA-based SOFC for less challenging fuels, such as natural gas, are in the sub-system development stage. The development of the SOFC stack is probably the pacing factor in overall SOFC development, even though some prototype systems have been constructed.

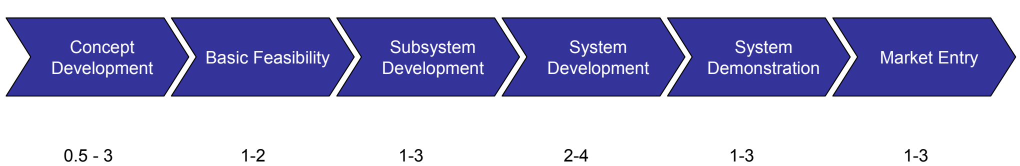


Figure 4-1 Overview of Stages of Development for Power Technologies (Ranges Indicate Minimum Time Required in Years)

The first generation of anodes and reformer catalysts more tolerant of sulfur and aromatic fuel components currently appear to be undergoing basic feasibility testing. Based on the timeframes shown in Figure 4-1, it would appear that sulfur- and aromatic-tolerant anodes and reformer catalysts would require 1-2 years to catch up with the rest of the technology. This may not significantly delay market introduction of diesel-fueled SOFC as further system development and demonstration will take at least three to five more years.

While it is possible that these first-generation technologies for diesel SOFC will work with ULSD, they appear unlikely to be sufficient for conventional diesel. If new concepts for conventional diesel will indeed be needed, it would take 3 to 8 more years until the new technology is ready for system integration. With that, it appears more likely that the development of new approaches for the use of conventional diesel would cause a significant delay in the market introduction of diesel SOFC.

Impact on Emissions and Energy Use

APUs for Heavy Duty Trucks, RVs, and Light Duty Vehicles

Market Characterization

Although the market for diesel APUs is currently modest, it could grow substantially if APUs are installed in a larger fraction of heavy duty trucks. Currently, diesel APUs are primarily used in RVs and yachts to provide power when the main engine is not needed for propulsion. For a discussion of the motivations and considerations for the use of APUs in various types of vehicles the reader is referred elsewhere [17, 25].

From a benefits perspective, RV and yacht applications are not very significant because the average activity (capacity factor) of the engines is estimated to be around 100 hours per year or less, even though there are estimated to be more than 100,000 units on the road [12, 26]. If the projected potential truck market is added to this, it could roughly quadruple the number of diesel APUs in the US by 2015 (to approximately 620,000 units). In addition, the truck APUs would have a load factor of about 0.4 but an activity level of about 2400 hours for long-haul trucks [25, 27].

If, unlike is the case with engines, diesel SOFC turn out to be only marginally more expensive than gasoline or LPG SOFC, and equally versatile, the market for diesel SOFC could be much larger, as a many of the current gasoline and LPG APU users may consider switching to diesel, which they may already be using for their main engine.

Impacts on National Benefits of SOFC

As the data in Table 4-1 shows, the main impact of the change in diesel regulations is the reduction in emissions from the diesel engine APUs. The diesel engine emission factors were taken from EPA's impact assessment for non-road diesel engines (which includes APUs) for the relevant years. As described in Chapter 3, currently non-road engines in this class must meet EPA Tier 1 regulations, and are allowed to operate on 2,000 ppm DF2. However, because these diesel APUs typically share the fuel tank with the main engine, APUs for RVs and trucks typically use the low sulfur (500 ppm) diesel that the main engine must use. Yachts are allowed to use conventional (2,000 ppm) diesel for their main engines, so consequently the APU too uses high sulfur diesel. The figures used are estimates of actual emissions factors, recognizing that actual emissions will actually be slightly lower than the regulatory limits. The heat rates of the engines increase slightly (by an estimated 2%) due to the impacts of EGR and DPF on engine efficiency. Conversely, SOFC efficiency improves slightly (by about 1%) because of the simplification of the balance of plant. The CO2 emissions scale linearly with the heat rate.

Table 4-1 Impact of Diesel Regulations on Per Unit National Benefits of SOFC in APU Applications [12]

	Current Diesel Regulations		US 2007 Regulations	
	Engine	**SOFC**	**Engine**	**SOFC**
NOx Emissions (g/kWh)	7.01	0.03	5.77	0.03
PM Emissions (g/kWh)	0.60	0.01	0.38	0.01
CO_2 Emissions (g/kWh)	1518	846	1548	823
Heat Rate	17,000	9,480	17,340	9,222

The cost SOFC APU is expected to be about the same as that of the engine-based APU for the current technology, assuming that SECA's system cost targets are met.

Table 4-2 Impact (Technical Potential) of Diesel Regulations on Total National Benefits of SOFC in APU Applications

Impact	Without New Diesel Regulations	With New Diesel Regulations
NO_x Emissions Reduction (T/yr)	24345	19998
PM 2.5 Emissions Reduction (T/yr)	2057	1274
CO_2 Emissions Reduction (million T/yr)	2.950	2.526
Diesel Fuel Consumption Reduction (million US gal/yr)	191	207

The total benefits, shown in Table 4-2, track the per unit impacts because the technical APU market potential of engines and SOFC remains the same with the new diesel regulations. The absolute reductions achieved in this market are very modest (about 1% to 2%) compared with overall emissions from non-road diesel engines, and even less when compared with all diesel engines.

Telecoms and Remote Industrial Applications

Market Characterization

The market for remote industrial applications of SOFC is quite fragmented. Of these, the application to provide baseload power to remote telecoms huts and signal signs have probably been most widely discussed as a potentially attractive market for fuel cells. Based on DOE and public data, the installed base for these markets combined is expected to be about 225,000 units by 2015 [12, 26]. On average, these units will be larger in capacity than the APUs, with an estimated average output capacity of about 9 kW.

Unlike the APU markets, units in these markets are heavily utilized, with load factors of around 0.43 and a utilization of around 6,000 hours per year [12, 26].

Impacts on National Benefits

The per-unit impacts for the telecoms and remote industrial market segment are about the same as for the APUs, except for the energy use benefits (Table 4-3.) Because the stationary engines used for these applications now are somewhat more efficient than the ones used in APUs (which are more optimized for space and weight), the benefit of SOFC per unit is somewhat more modest in this application. However, because the efficiency of the engines is closer to that of the SOFC, the relative impact of the changes in efficiency that result from the new regulations is greater.

Table 4-3 Impact of Diesel Regulations on per Unit Benefits of SOFC in Remote Telecoms and Industrial Applications [12, 26]

	Current Diesel Regulations		US 2007 Regulations	
	Engine	**SOFC**	**Engine**	**SOFC**
NOx Emissions (g/kWh)	7.01	0.03	5.95	0.03
PM Emissions (g/kWh)	0.60	0.01	0.38	0.01
CO_2 Emissions (g/kWh)	1,250	846	1,275	823
Heat Rate	14,000	9,480	14,280	9,222

The impact on the total benefits again tracks the per-unit benefits. In this application it is unlikely that the availability of SOFC or the new regulations would significantly impact the technical market size. The benefits are, in absolute terms, in the same range as those for the APU applications, and consequently also modest compared with the total emissions from diesel engines.

Table 4-4 Impact (Technical Potential) of Diesel Regulations on Total Benefits of SOFC in Remote Telecoms and Industrial Applications

Impact	Without New Diesel Regulations	With New Diesel Regulations
NO_x Emissions Reduction (T/yr)	42423	35989
PM 2.5 Emissions Reduction (T/yr)	3584	2220
CO_2 Emissions Reduction (million T/yr)	2.452	2.743
Diesel Fuel Consumption Reduction (million US gal/yr)	200	224

Mobile Generators

Market Characterization

A wide range of diesel engine applications are included in this category. Though such generators are used in capacities ranging from about 3 kW up to well over 1 MW, the focus here is on the category smaller than 37 kW (or 50 hp.) Ultimately SOFC may be applied to the larger diesel generator categories. The biggest sub-categories in this application market are mobile electrical generators, diesel-powered refrigeration and air conditioning units, and pumps. Together, these markets are estimated to represent an installed base of over 2 million units by 2015 [12, 26].

Mobile generators are used in a wide range of capacities, but in the range considered here the average output capacity is around 24 kW. Although some of these units are undoubtedly operated in a duty cycle close to baseload, on average the load factor is average (0.43) and the utilization is modest (about 680 hours per year.)

Impacts on National Benefits

As shown in Table 4-5 the impact on emissions reductions per unit for these engines is significantly greater than in the smaller engine categories for the previous two market applications discussed. The new diesel regulations require that these engines apply a diesel particulate filter plus EGR for emissions control, similar to Euro 4 on-road diesel standards. As a consequence, the particulates reduction benefit of SOFC is all but eliminated [12]. As these larger engines are more efficient, the fuel savings benefit is further reduced, but the relative impact of the new regulations on fuel savings is relatively greater.

The impact on the total benefits for Mobile Generator applications are shown in Table 4-6, and reflect the per unit trends. Because these units have relatively low capacity factors, compared to APUs and industrial applications, the total impact is not as great as the large installed base may suggest.

Table 4-5 Impact of Diesel Regulations on per Unit Benefits of SOFC in Mobile Generators [12]

	Current Diesel Regulations		US 2007 Regulations	
	Engine	**SOFC**	**Engine**	**SOFC**
NOx Emissions (g/kWh)	5.95	0.03	4.02	0.03
PM Emissions (g/kWh)	0.36	0.01	0.02	0.01
CO_2 Emissions (g/kWh)	1,116	846	1,138	823
Heat Rate	12,500	9,480	12,750	9,222

Table 4-6 Impact (Technical Potential) of Diesel Regulations on Total Benefits of SOFC in Mobile Generator Applications

Impact	Without New Diesel Regulations	With New Diesel Regulations
NO_x Emissions Reduction (T/yr)	83900	56500
PM 2.5 Emissions Reduction (T/yr)	4200	200
CO_2 Emissions Reduction (million T/yr)	3.82	4.46
Diesel Fuel Consumption Reduction (million US gal/yr)	43	50

Small Non-Road Vehicles

Market Characterization

Small diesel engines are used in a wide variety of, mostly industrial, non-road vehicles. These vehicles are mostly multi-purpose vehicles. Included in this analysis are a number of non-road vehicle classes with engines smaller than 19 kW (25 hp.) These include agricultural and landscaping equipment (agricultural tractors, lawn-mowers, turf equipment), construction equipment (skid-steer loaders, excavators, tractor loaders, wheel loaders, rollers, and rough terrain forklifts), and materials handling equipment (forklifts, aerial lifts, and utility vehicles.) In most of these classes, units with engines less than 19 kW represent the mini-versions, while standard versions have engines of around 100 kW and more. Collectively, the class analyzed represents sales of about 45,000 units per year and an estimated installed base of just over 500,000 units by 2015 [12, 26]. While engine capacities vary, in the less than19 kW range the weighted average engine capacity for these units is about 15 kW.

The uses and duty cycles of these vehicles vary dramatically, leading to an average load factor of 0.46 and an average activity level of 600 hours per year. Also, because some of the systems are used intermittently, there may be segments of this market that are technically difficult to penetrate for SOFC [12, 26].

Impacts on National Benefits

According to EPA analysis for their non-road regulatory impact assessment, 2003 model year engines in this class already meet Tier 4 standards (Table 4-7). This apparent peculiarity appears to have arisen because under Tier 1 regulations these engines are grouped with larger engines (which are regulated more stringently); while in the Tier 4 regulations they are grouped with much smaller engines (which are regulated less stringently.) For this class of engines, the impact of the new regulations is non-existent.

The change in fuel quality would still allow for a reduction in the heat rate of the fuel cell systems.

Table 4-7 Impact of Diesel Regulations on per Unit Benefits of SOFC in Non-Road Vehicles [12]

	Current Diesel Regulations		US 2007 Regulations	
	Engine	**SOFC**	**Engine**	**SOFC**
NOx Emissions (g/kWh)	5.95	0.03	5.95	0.03
PM Emissions (g/kWh)	0.36	0.01	0.36	0.01
CO_2 Emissions (g/kWh)	1,205	846	1,205	823
Heat Rate	13,500	9,480	13,500	9,222

Due to the low activity level of this equipment, the overall total benefits of diesel SOFC in this market segment is also limited (Table 4-8).

Table 4-8 Impact (Technical Potential) of Diesel Regulations on Total Benefits of SOFC in Non-Road Vehicles

Impact	Without New Diesel Regulations	With New Diesel Regulations
NO_x Emissions Reduction (T/yr)	15900	15900
PM 2.5 Emissions Reduction (T/yr)	935	935
CO_2 Emissions Reduction (million T/yr)	0.97	1.03
Diesel Fuel Consumption Reduction (million US gal/yr)	11	12

Summary

Overall, the potential national emissions benefits of diesel SOFC in the selected four markets is reduced by up to 40% by the introduction of new diesel regulations, while the energy savings benefits are increased by up to 15%. These benefits depend on the application and especially on the engine capacity. Because of changes in the classification, some categories see a 90% reduction in PM emissions benefits while others see no change at all.

Quantitatively, the total impact of all of the application markets combined is shown in Table 4-9. Placed in perspective of all diesel use, the changes in NOx and PM benefits are considerable on a relative basis. However, when compared with the impacts of all diesel use, the numbers represent less than one percent of energy use, and no more than 5% of criteria pollutant emissions.

Table 4-9 Summary of Impact (Technical Potential) of Diesel Regulations on Total Benefits of SOFC in all Markets Combined by 2015

Impact	Without New Diesel Regulations	With New Diesel Regulations
NO_x Emissions Reduction (T/yr)	166,600	128,400
PM 2.5 Emissions Reduction (T/yr)	11,500	4,600
CO_2 Emissions Reduction (million T/yr)	7.24	8.23
Diesel Fuel Consumption Reduction (million US gal/yr)	445	492

Impact on Cost and Competitiveness

The changes in diesel fuel regulations have a number of positive impacts on the cost-competitiveness of diesel SOFC:

The direct manufactured cost of diesel SOFC equipment is expected to be reduced by about $100 per kW, while the cost of competing engines in these small-capacity classes is projected ([24]) to be around $20 per kW. This would move diesel SOFC from a position of cost disadvantage compared with engines to one of cost advantage.

- The impact of new regulations does not appear to significantly change any difference O&M cost between diesel SOFC and diesel engines. Operating and maintenance cost for SOFC would be reduced due to the introduction of ULSD, mostly because the sulfur cartridge exchange interval will be stretched by a factor of ten. However, this impact would likely be minor (less than 10%) when compared to the major component of SOFC maintenance: stack replacement. EPA carried out a relatively detailed analysis of the impact of proposed regulations on diesel engine operating cost and concluded that the impact would range from an approximately 10% cost savings for the smallest systems to an approximately 5% cost increase for somewhat larger systems that have light duty cycles;

- If SECA cost targets are met, gasoline and diesel SOFC may be (practically) interchangeable with ULSD. Both from a cost and a functionality perspective this provides a major advantage for SOFC in a number of markets, notably APUs.

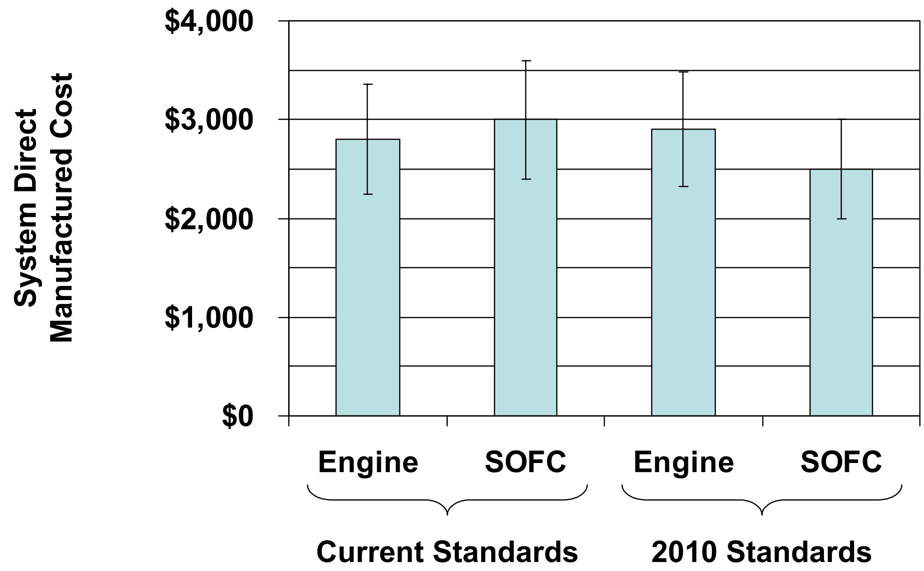


Figure 4-2 Comparison of Equipment Cost for Diesel Engines and SOFC under Current and 2010 Standards (Projected based on Arthur D. Little [17] and EPA studies [12])

It is likely that the improvement in the cost-competitiveness of diesel SOFC resulting from the introduction of new diesel regulations would more than off-set the reduced environmental benefits (and hence the strength of the environmental driver.) Generally, market penetration of new technologies is much more rapid if it is based on a cost advantage than if it is based on an emissions advantage (unless of course it is subject to forcing regulations.)

5 Conclusions and Recommendations

Conclusions

The review of diesel specifications and diesel engine emissions standards that go into effect over the next seven years reveals that most diesel fuel sold in the US and Europe will have substantially lower sulfur (10 – 15 ppm) by 2010. This will likely include a substantial portion, if not all of the non-road diesel market. In addition, in some markets aromatics and PAH levels will be reduced considerably.

The changes in diesel fuel specifications will facilitate the development of diesel SOFC technology, but even with the new technologies, the need for more sulfur-tolerant reformers and anodes persists. Nevertheless, the introduction of ULSD makes it much more likely that functional and competitive diesel SOFC technology will be developed in the next ten years.

In addition, the analysis indicated that the lower sulfur content in diesel will virtually eliminate the cost-penalty for diesel-SOFC (which may be about $100/kW if CARB diesel were to be used.) In fact, a diesel SOFC designed for ULSD will likely be substantially the same as one designed for operation with gasoline. This could substantially broaden the appeal of SOFC compared with diesel engines. To the extent that aromatics levels are changed, the changes will likely not be sufficient to substantially alter the design, operation, or cost of diesel SOFC systems.

As new diesel engine emissions standards will drive the application of novel technologies they will reduce emissions of NOx and PM, while increasing cost by $15 to $45 per kW. The impact on engine efficiency is expected to be minor.

Despite the drastic nature of the changes in fuel specifications and engine emissions standards, the changes are small compared with the emissions and efficiency differences between engines and SOFC. As a consequence, there is no general change in the motivating factors for the development of SOFC.

This analysis shows that combined, these impacts of the new diesel regulations on both SOFC and engines have several consequences for the national impacts of the use of diesel SOFC in selected small-capacity (less than 56 kW) SOFC applications (including APUs, mobile generators, remote telecoms and industrial power, and small non-road vehicles):

- The criteria pollutant emission benefits from SOFC are reduced as the engines that they replace become substantially cleaner. Still, SOFC will be substantially cleaner than the competing engine technologies;
- The reductions in energy use and greenhouse gas emissions that result from the use of diesel SOFC are maintained and in some cases increased;
- The cost comparison between high duty cycle diesel engines (i.e. not stand-by generators) and diesel SOFC will change in SOFC's favor due to the new regulations.

The most uncertain portion of the implications of new diesel regulations for diesel SOFC lies in military applications. Based on current DOD policies and practices, JP-8 will still be used as the single battlefield fuel beyond the 2010 timeframe. As no changes in specifications are expected, there will be a growing discrepancy between JP-8 specifications and those for civilian diesel fuels. This will mean that by 2010, JP-8 will not be compatible with much of civilian diesel engine technology or with civilian SOFC technology. As the DOD has recognized in its desire for the development and adaptation of dual-use technology by the military, this will likely raise the cost of engines and SOFC for the military, as they will have to be specially developed for the armed forces. Also, it is not clear how the military will meet domestic environmental regulations for its operations. Several groups within the DOD have started to address this challenge.

Recommendations for DOE

Although DOE's SECA program is already well-positioned to help prepare the SOFC industry for the 2010 diesel regulatory situation (DOE has already considered the expected changes in its program planning), there are additional actions that could be taken to focus the program even better on the future regulatory situation:

- Development work on advanced anodes should focus on the most relevant sulfur levels:
  - ☐ For most applications, the target should be on fuels that will have a fuel sulfur limit of 15 ppm, indicating that tolerance to around 5 ppm gas-phase sulfur (including some safety margin) would suffice;
  - ☐ Tolerance to 100 ppm or 1000 ppm sulfur would continue to be relevant for certain international markets, military applications and other niche markets where high-sulfur diesel is still used;
- Several basic parametric studies combining experiment with analysis could accelerate both materials and stack development:
  - ☐ Impact of sulfur type and temperature on sulfur tolerance
  - ☐ Impact of fuel composition and operating conditions on coking in the stack

- At some stage, a subset of the type of data generated in these parametric experiments mentioned above should be part of most electrode, reformer catalyst, and stack development programs.

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