Diesel Fuel Additives: Use and Efficacy for Alaska's Diesel Generators

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Prepared for the Alaska Energy Authority

May 2013
Report No.: INEacep13.05

ACEP Alaska Center for Energy and Power

UAF University of Alaska Fairbanks

Acknowledgments

Individuals working in power plants across Alaska openly gave us meaningful insights into their site-specific operations. We gratefully acknowledge their contributions to the grounding of the report in actual experiences related to purchase, delivery, and efficacy of use of diesel fuel additives. Throughout the study, the contacts, personal wisdom, and overview provided by the Stakeholder Advisory Committee members opened lines of investigation and gave cause for judicious reflection on the whole spectrum of claimed benefits, observed effects, and integration of additives into the diesel fuel supply chains available to those operating stationary diesel-driven generators.

Incredible depth and perspective on best practices for additive utilization was provided by John Eason, thus helping frame the discussions of beneficial mixing and use of some additives to meet the needs in Alaska power plants. David Light shared knowledge beyond his years to help us fully understand and appreciate not only how the diesel engines found in power plants work, but also the context of their operation in remote sites. Mark Reischke shared perspectives on diesel fuel production, introduction of additives, and rigorous testing of fuel products that proved influential in understanding the way things are done in Alaska. He also graciously gave us permission to use some of the photographs used in this report.

Bob Dryden shared an amazing depth and breadth of knowledge of the process by which consortia specify and purchase fuel. The knowledge passed on to us deeply affected how we viewed all aspects of diesel fuel provisioning in Alaska. This study would not have been accomplished without Meera Kohler's persistent questioning of the value of additives marketed to improve diesel fuel properties. The careful and helpful management of the project by Alan Baldivieso of the Alaska Energy Authority encouraged us throughout this phase of the study.

Front cover photo:

Adding an additive to Yakutat Power's diesel fuel tank. Photo by Scott Newlun.

Back cover photo:

Barge delivery of fuel/additive by Vitus Marine. Photo courtesy of Vitus Marine.

To cite this report:

Kemp, C., Williams, F., Holdmann, G., & Witmer, D. (2013). Diesel Fuel Additives: Use and Efficacy for Alaska's Diesel Generators. Report No. INEacep13.05, Alaska Center for Energy & Power, University of Alaska Fairbanks.

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Executive Summary

Rural Alaska communities remain dependent on diesel generators to provide electricity, albeit at costs significantly higher than costs in grid-connected communities. Reducing those costs through improving engine efficiency and/or reducing engine maintenance, is a high priority for those responsible for these systems. Significant improvements in diesel engines over the past few decades, especially the introduction of electronically controlled injection systems and higher compression turbo chargers, have led to much more efficient diesel operation. However, one can always hope to do better, and some have suggested that additional efficiency gains can be realized through the use of diesel fuel additives.

For the purpose of this study, an additive is a chemical mixture that is added to a diesel fuel in order to change the fuel's properties, with the intention of improving the performance of a diesel engine. In this report, we assess the current use of diesel fuel additives in the Alaska electric utility industry, with special focus on evaluating fuel additives for the possibility that they might improve fuel economy of rural diesel electric generators. Information was gathered about fuel sources and distribution networks, additives used by fuel suppliers, experiences of electric utility operators with additives, the performance of additives anticipated by additive suppliers, recommendations of diesel engine manufacturers, peer-reviewed journal articles, and other public sources including the EPA.

Diesel fuel is a mixture of hydrocarbons that has properties necessary for the sustained operation of a diesel engine. To accomplish that, standard fuel specifications are set, requiring many properties of the fuel to be in an acceptable range, including flash point, pour point, viscosity, and lubricity. These specifications, and many others, are given in ASTM D975, Standard Specifications for Diesel Fuel Oils. All engine manufacturers require the use of ASTM D975 fuels, and do not recommend the routine use of any additional additives.

Diesel fuels are most commonly distilled from crude oils, a mixture that may vary considerably in composition, and the product is sometimes adjusted at the refinery to bring the fuel into specification. This may be done either through a refining process (such as the removal of sulfur in the production of Ultra Low Sulfur Diesel (ULSD) or by use of additives. ASTM D975 permits and, in fact, sometimes requires the use of additives to bring fuels into proper specifications. Examples are the use of conductivity and lubricity additives for ULSD fuels, and the use of pour point depressants to adjust for local geographic conditions, such as those found in Alaska during the winter.

The point in the fuel delivery stream where additives are mixed with the fuel varies depending on the properties of the additive and transport constraints. No guidance for mixing is specified by ASTM D975. Pour point depressants are most effectively added at the refinery, because a less expensive additive can be used to give better results if the additive is mixed with hot fuel. On the other hand, lubricity additives for treating Ultra Low Sulfur Diesel (ULSD) fuels are often added when transferring fuel from the barge to the bulk fuel storage tanks, because the lubricity additives are hygroscopic (attract water from the atmosphere.) If the additive were in the fuel during barge transport, there would be increased potential for water contaminating the fuel. Other additives, such as injector cleaners or biocides might be added anywhere in the delivery stream to treat specific issues that develop in utility operation.

In addition to the additives discussed above, many other products are available for treating diesel fuel, some of which claim to significantly improve (10-20%) the efficiency of diesel engines. Often these claims are supported by testimonials or reports that purport to verify these statements. However, reviewing the claims raises cause for concern, including: testimonials based on very short term experience, reports that appear to have been edited or altered after their creation, and the lack of signatures or certifications by the testing organizations. Often, links to patents or studies are missing, or no information is given at all. Complicating these claims is the fact that under normal operation, fuel consumption and power generation efficiencies vary due to factors not always accounted for, including temperature, load variation, changes in fuel properties, and maintenance history among other things. Marketing efforts tend to use only those studies that show a positive effect; studies that show either no effect or negative effects are simply not presented.

Attempting to test products with sufficient rigor to establish the veracity of their claims is a significant and costly undertaking, especially if long-term costs or benefits are to be experimentally evaluated. There is one testing program in the U.S. dedicated to evaluating efficiency additives and retrofit devices. The program was founded in 1971 and is run by the EPA. A quote from their web site addresses the results of their studies:

> *If a marketed device [claims to have] significant benefits, the manufacturer may submit data to the EPA and apply for EPA testing through the Voluntary Aftermarket Retrofit Device Evaluation Program. Very few manufacturers have applied for this program in the past 10 years. Most devices tested in earlier years had a neutral or negative effect on fuel economy and/or exhaust emissions.*

No similar program has been identified for additives specifically designed for diesel engine fuels, but many additives and devices claim to provide benefits in both gasoline and diesel engines. None of the products currently marketed in Alaska have been identified as participating in the EPA testing program. The testing program is distinct from the EPA registration program. EPA registration verifies that a diesel additive does not violate emission regulations but does not provide any analysis of its efficacy.

Some fuel additives, such as those identified for pour point depression and lubricity additives for ULSD fuels, are necessary for bringing fuels into ASTM D975 compliance. Other additives, such as biocides, might be useful for long-term storage of diesel fuels in damp climates. Some engines not operating at optimal performance may benefit from an injector or fuel system-cleaning additive. But in general, the engine manufacturer's recommendation that no additives be used in diesel fuels appears to be sound advice.

Our survey of utilities in Alaska indicated that most operators understand the need for pour point management and ULSD lubricity additives, and are purchasing fuel adequately treated for these properties. Some utilities routinely and appropriately use biocides. Other utilities blend lubricity additives into their fuel onsite, which may add an unnecessary cost to their operation, given that fuel distribution companies only deliver ULSD fuel that has already been treated and meets the ASTM lubricity specification. Some utilities do use multipurpose additives that include lubricity and injector cleaning detergent agents, although they are branded as efficiency boosters.

Proper use requires good mixing of additives into the fuels, with increased attention the closer the point of introduction of the additive is to the utility. Adding additives to fuel tanks adjacent to the power plant requires attention to the physical mixing, temperatures of the fuel and the additive, and the mixing ratio. These conditions are often better controlled during delivery of the fuel to the region, and best controlled by the fuel producer or bulk distributor.

A handful of Alaska utilities have also experimented with additives or aftermarket devices intended to improve efficiency. While two out of seven users reported some positive results, neither could, with certainty, provide an economic analysis of the benefits of such devices, or appeared willing to recommend their widespread use to other utilities.

Modern, well-maintained diesel engines operate at very high thermodynamic efficiency levels. Fuel efficiencies achieved in large diesel engines are at, or are very close to, the maximum achievable. Fuel efficiencies associated with electrical power production from smaller engines generally cannot match those of larger engines because of physical design considerations combined with theoretical maximum combustion cycle efficiency constraints. Theoretical and experimental reports support the assertion that additives cannot, and therefore have not, been documented to improve fuel efficiency in well-maintained engines.

While not replacing the need for regular maintenance, additives may clean engine components that show degraded performance because of the build-up of deposits. This may well be more valuable for older technology engines, as well as engines long into their prescribed maintenance cycle, as a means for restoring original performance. Therefore, we recommend continuing to assess the need for cleaning agents in fuels, and the appropriate use of those kinds of additives in engines of all ages to help ensure long engine life and new-engine performance.

To date, the authors of this report have found no credible information from any of our sources to support the claim that any product can improve the operating efficiency above that of a well-maintained diesel engine. We recommend *bona fide* testing of additives where controlled conditions can be insured. Use of test facilities and rigorous protocols will increase the understanding of the efficacy of—and improve the credibility of—

representations of additives. At this time, no candidate additive for improving fuel efficiency has been identified for such extensive laboratory testing. However, augmenting testing of additives or add-on devices at utility sites by use of unbiased, third-party analysts could bring more understanding to the testing and help identify promising additives.

Introduction

Rural Alaska communities remain dependent on diesel generators to provide electricity, albeit at costs significantly higher than costs in grid-connected communities. Reducing those costs, either through improving engine efficiency or reducing the maintenance, is a high priority for those responsible for these systems. Significant improvements in diesel engines over the past few decades, especially the introduction of electronically controlled injection systems and higher compression turbo-chargers, have led to much more efficient diesel operations. However, one can always hope to do better, and some have suggested that additional efficiency gains can be realized through the use of diesel fuel additives.

Premise

Many vendors actively market diesel fuel additives purported to decrease fuel consumption, reduce emissions, and extend maintenance periods and mean time to failure for stationary diesel engines. Evaluating these claims is difficult, as fuel properties, diesel engine types, operating parameters, and other factors may affect the observed performance. Often there is little or no credible information documenting claims of beneficial effects, but profuse anecdotal information and testimonials that can seem compelling are routinely proffered. The authors do not *a priori* discount the possibility that some of these fuel additives could positively affect engine performance. Whether or not there are any positive benefits, the uncertain value of using additives, and the high prevalence of marketing additives in Alaska warrant a more systematic, comprehensive approach to addressing these products. An unbiased review and assessment of known products by an organization able to assess new products as they are marketed to Alaskans should well serve the diesel fuel user communities.

There are over 200 communities in Alaska served by diesel generators. These communities are geographically distributed throughout the state. In addition, there are a number of industrial users of diesel generator sets (gensets) for primary and secondary electrical power generation. Typically, fuel additive vendors claim increases in diesel efficiency of 10-15%. If this increased efficiency were demonstrated to be real, savings could be substantial. In fiscal year 2009, utilities participating in Power Cost Equalization (PCE) consumed in excess of 29 million gallons of diesel fuel for electrical power generation. A proposed benefit of 10% savings would represent an annual savings of almost 3 million gallons representing a cost savings of greater than $10,000,000 (assuming a conservative fuel cost of $3.50 per gallon). The net savings could be between $7 million and $8.5 million given the nominal cost associated with these fuel additives. On the other hand, if the products are not effective and/or damage engines, the net result is more expensive energy.

Quantifying the potential benefit of additives that portend to extend maintenance periods and mean time to failure is more difficult, but nonetheless extremely valuable to utilities in the state. Utilities routinely seek new ways to improve the cold temperature performance of their plants, to avoid unnecessary engine wear, and to prevent fuel contamination. Additives can play an important role in all these enterprises, yet it remains unclear to many utilities when these products should be used, which products can provide legitimate benefits, and how the products can be blended with the fuel most effectively. Compiling an overview of the different types of additives and their appropriate applications in Alaska will provide a useful guide for utilities.

Approach

This study is based on information we gathered about the use of diesel fuel additives in Alaska, including the experiences of many of the rural power utilities. We contacted vendors of diesel fuel additives who are active in Alaska, discovered how fuel (and any additives included in fuel delivery) is procured and distributed across the state, reviewed literature including pertinent federal agency reports, and interviewed known experts on the use of additives.

To help ensure that this study covers the essential elements in determining the efficacy of use of diesel fuel additives in Alaska's power utilities, a Stakeholder Advisory Committee was formed. The Stakeholder Advisory Committee represented users at power utilities, large-scale procurers of fuel, bulk deliverers of fuel, and the Alaska Energy Authority's diesel generation expertise.

The report first discusses diesel fuel properties, then discusses additives used in diesel fuel, categorized by function. The discussion then advances to Alaska-specific topics: how fuel is purchased and delivered, where in this distribution chain additives are likely to be used, and by whom.

Background and Literature Review

In order to understand the context for the use of additives in diesel fuel, a review of the literature was undertaken. Materials reviewed included: properties of diesel fuels; ASTM D975, Standard Specifications for Diesel Fuel Oils; information on common diesel fuel additives; and a review of current diesel engine performance specifications. In addition, general comments about the use of additives in Alaska conditions are given.

Diesel Fuel

Diesel fuel is defined as any fuel intended for sustained operation in a diesel engine. That definition means diesel fuel can contain a mixture of an enormous variety of chemicals from various sources: as long as the collection of chemicals can power a compression ignition engine, it is considered diesel fuel. Diesel fuel can be distilled from crude oil, refined from vegetable oils, or created synthetically from coal or natural gas [2]. These fuels may include n-paraffin molecules (carbon and hydrogen chains 5 to more than 50 atoms long), and aromatics (one or more rings of carbon atoms bonded with hydrogen atoms) [3]. Hydrocarbons representing those kinds of molecules are depicted in Figure 1. The concentration of the various types of hydrocarbons in diesel fuel is not specified directly, and varies between biofuels, synthetic fuels, and crude oils, and even between crude oils from different reservoirs. As a result, the efficacy of additives varies depending on the source of diesel fuel, and on the feedstock it is derived from.

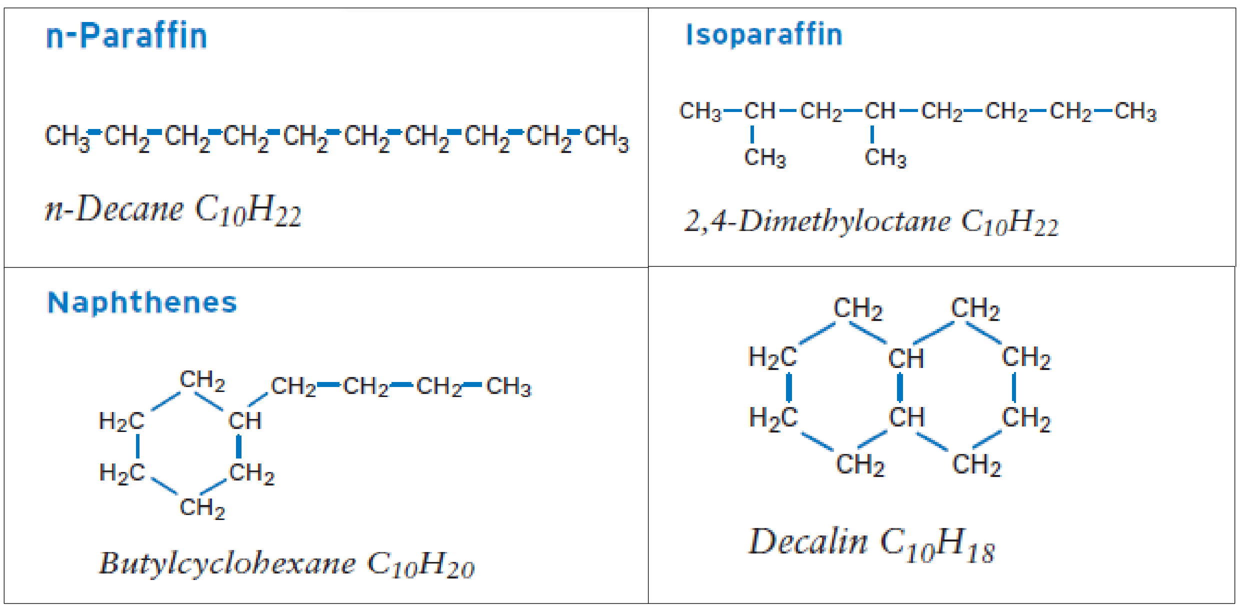

Figure 1. Four compounds commonly found in diesel fuels. Reproduced from [3].

Diesel fuel refined from crude oil (sometimes referred to as “petro diesel”) is by far the most common. Crude oils are liquid mixtures of hydrocarbons that vary widely depending on their source. Crude oil can be refined and distilled to separate out the diesel fuel grade components, contained in the fraction distilled between 200°C (392°F) and 350°C (662°F), corresponding to molecules with between 8 and 21 carbon atoms. Diesel fuel molecules are heavier and less volatile than those found in gasoline, and therefore have a higher flash point. For this reason, diesel fuels are safer to transport and store.

There are many similar distillate fuels, including kerosene, jet fuel, heating oil, stove oil, and bunker fuels (typically used by ships). In many cases, a refinery can produce a distillate product that can be sold as any of a number of these fuels, since these fuels differ only by handling processes and additive packages. For example, jet fuel, diesel fuel, and heating oil are quite similar, except that jet fuel must be shipped in clean containers and special efforts must be made to prevent the introduction of water into the fuel. Diesel fuels must provide adequate lubricity for proper engine operation and have the proper compression ignition point. Heating fuels simply need to burn in a boiler. If jet fuel becomes contaminated, it is often sold, at considerably lower value, as heating oil.

ASTM D975 Standard Specification for Diesel Fuel Oils

Diesel fuels must meet a wide variety of specifications to ensure they are appropriate for the diesel engines and locations they are used in. The most commonly referenced standard for determining those properties and classification of diesel fuels in general is the ASTM D975 Standard Specification for Diesel Fuel Oils [4]. ASTM International (formerly the American Society for Testing and Materials) is a nonprofit organization that writes voluntary industry standards. Although there is no legal requirement that fuels meet the ASTM standards, refineries generally guarantee that their fuel meets the standards in order to affirm their products' quality, and larger purchasers require that fuel meet these standards. ASTM D975 defines seven grades of diesel fuel depending on distillation temperature, Cetane number, and sulfur content (see Table 1), and incorporates more than 50 standard testing procedures to determine fuel properties. Diesel fuel No. 1 is a lighter grade of fuel, similar to kerosene, while diesel fuel No. 2 tends to be a heavier grade, with a higher energy content per unit volume.

As shown in Table 1, ASTM D975 defines a minimum or maximum value for most properties, but allows a range of values. In some cases, such as cloud point and pour point, the standard depends on expected minimum temperatures, and varies by geographic region and season. ASTM D975 specifically references, permits, and sometimes requires the use of additives: for long-term storage (Appendix X3.4), for improved lubricity (Appendix X4.3), and for cold flow improvement (Appendix X5.1.3). It is important to ensure that the additives be carefully chosen so that they do not cause the fuel to go out of spec with regard to other properties (for example, some early proposed lubricity additives contained enough sulfur to violate the ULSD standard).

The Environmental Protection Agency (EPA) recently introduced a requirement that diesel fuels for on-road use be Ultra Low Sulfur Diesels (ULSD). Since distillate fuels may have up to 5000 ppm sulfur, reducing this to the ULSD standard of 15 ppm requires additional refining steps, and special care in shipping and storage to maintain the low sulfur content. The new ULSD standard allows lower particulate emissions and the use of engine after-treatment for reduction in emission of NO_x. However, removal of the sulfur from the fuel also removes much of the natural lubricity and conductivity of the diesel fuel, requiring the use of additives to minimize engine wear and prevent static charge from building during fuel pumping that could ignite the fuel.

Table 1. Fuel properties specified by ASTM D975. Table adapted from ASTM D975-12 [4].

Property	ASTM Test Method	Fuel Grade No.						
		1-D S15	1-D S500	1-D S5000	2-D S15	2-D S500	2-D S5000	4-D
Flash Point, °C, min	D93	38	38	38	52[a]	52[a]	52[a]	55
Water and Sediment, % vol, max	D2709	0.05	0.05	0.05	0.05	0.05	0.05	
	D1796							0.50
Distillation Temperature, °C 90% vol recovered								
Min	D86				282[a]	282[a]	282[a]	
Max	D86	288	288	288	338	338	338	
Kinematic Viscosity, mm^2/S at 40°C								
Min	D445	1.3	1.3	1.3	1.9[a]	1.9[a]	1.9[a]	5.5
Max	D445	2.4	2.4	2.4	4.1	4.1	4.1	24.0
Ash, % mass, max	D482	0.01	0.01	0.01	0.01	0.01	0.01	0.10
Sulfur, ppm (µg/g)[b] max	D5453	15			15			
% mass, max	D2622		0.05			0.05		
% mass, max	D129			0.5			0.5	2.00

Property	ASTM Test Method	Fuel Grade No.						
		1-D S15	1-D S500	1-D S5000	2-D S15	2-D S500	2-D S5000	4-D
Copper strip corrosion rating, max (3 h at a minimum control temperature of 50°C)	D130	No. 3	No. 3	No. 3	No. 3	No. 3	No. 3	
Cetane Number, min	D613	40[c]	40[c]	40[c]	40[c]	40[c]	40[c]	30[c]
One of the following properties must be met:								
(1) Cetane Index, min.	D976-80	40	40		40	40		
(2) Aromaticity, % vol, max	D1319	35	35		35	35		
Operability Requirements								
Cloud Point, °C, max	D2500	[d]	[d]	[d]	[d]	[d]	[d]	
OR LTFT/CFPP, °C, max	D4539/D6371							
Ramsbottom Carbon Residue on 10% Distillation Residue, % mass, max	D524	0.15	0.15	0.15	0.35	0.35	0.35	
Lubricity, HFRR @ 60°C, micron, max	D6079/D7688	520	520	520	520	520	520	
Conductivity, pS/m or Conductivity Units (CU), min	D2624/D4308	25[e]	25[e]	25[e]	25[e]	25[e]	25[e]	

[a] When a cloud point less than −12°C is specified, as can occur during cold months, it is permitted and normal blending practice to combine Grades No. 1 and No. 2 to meet the low temperature requirements. In that case, the minimum flash point shall be 38°C, the minimum viscosity at 40°C shall be 1.7 mm^2/s, and the minimum 90% recovered temperature shall be waived.

[b] Other sulfur limits can apply in selected areas in the United States and in other countries.

[c] Low ambient temperatures as well as engine operation at high altitudes may require the use of fuels with higher cetane ratings.

[d] It is unrealistic to specify low temperature properties that will ensure satisfactory operation at all ambient conditions. In general, cloud point (or wax appearance point) Low Temperature Flow Test, and Cold Filter Plugging Point Test may be used as an estimate of operating temperature limits for Grades No. 1–D S500; No. 2–D S500; and No. 1–D S5000 and No. 2–D S5000 diesel fuel oils. However, satisfactory operation below the cloud point (or wax appearance point) may be achieved depending on equipment design, operating conditions, and the use of flow-improver additives as described in Appendix X5.1.2. Appropriate low temperature operability properties should be agreed upon between the fuel supplier and purchaser for the intended use and expected ambient temperatures. Due to fuel delivery system, engine design, and test method differences, low temperature operability tests may not provide the same degree of protection in various vehicle operating classes. Tenth percentile minimum air temperatures for U.S. locations are provided in Appendix X5 as a means of estimating expected regional temperatures. The tenth percentile minimum air temperatures can be used to estimate expected regional target temperatures for use with Test Methods D2500, D4539, and D6371.

[e] The electrical conductivity of the diesel fuel is measured at the time and temperature of the fuel at delivery. The 25 pS/m minimum conductivity requirement applies at all instances of high velocity transfer (7 m/s) but sometimes lower velocities, see Section 8.1 of ASTM D975 for detailed requirements) into mobile transport (for example, tanker trucks, rail cars, and barges).

What Are Diesel Fuel Additives?

Diesel additives are chemicals that do not naturally occur in distilled crude oil based diesel fuels, but are blended with the fuel to improve its properties. Additives address a broad range of needs, as summarized in Table 2. Additives may be blended into the fuel at the refinery, added during bulk fuel delivery, added by a utility to a bulk tank or a day tank, or used by an individual consumer to treat a small tank of fuel.

Table 2. A description of the most common additives in Alaska and their intended functions. Notes: NR= Not Recommended, (1) AK utilities use warm fuel to eliminate wax particles and do not generally specify cloud point, (2) Injector cleaner use may be warranted if injector fouling is suspected.

Additive Type	Function	ASTM D975	Utility
Biocide	Kill or prevent biological growth in fuel tanks	Permitted	AK use
Cetane Boost	Increase the Cetane number of a fuel	Permitted	Rarely used
Conductivity	Increase the conductivity of fuel to reduce the risk of static charge buildup	Required for ULSD	Used by refiners
Cloud Point Depressant	Decrease Cloud point	Permitted	(1)
Efficiency Boost	Increase the efficiency of an engine	Not addressed	Rarely used
Emissions	Reduce pollutant emissions	Not addressed	Rarely used
Injector Cleaner	Clean fuel injectors	Not addressed	(2)
Lubricity	Increase fuel lubricity	Required for ULSD	AK Use
Pour Point Depressant	Decrease the pour point	Permitted	AK Use
Stabilizer	Improve the storage stability of fuel	Permitted	Rarely used
Water Disperser	Disperse water in fuel. Intended to allow the water to be evaporated during combustion while the fuel burns.	NR	NR

EPA Registration of Diesel Fuel Additives

To sell diesel or gasoline additives for use in vehicles in the U.S., companies must register them with the EPA. The purpose of the EPA registration process is to prevent the sale of additives that would release hazardous pollutants; it does not confirm that the product offers any benefit to consumers. Vendors are required to disclose their products' contents to the EPA for registration, as commercial packaging for these products generally does not include any information for the consumer about what is contained in the product.

Over 4,000 diesel fuel additives are registered with the EPA by 686 different companies [5]. These products claim to improve an enormous range of fuel properties, from the conductivity of diesel fuel to the resistance of the fuel to biological growth. The products serve different markets as well: some are purchased by refiners or fuel shippers in bulk and blended with fuel before it leaves the refinery, while others are purchased at local gas stations in pint-sized bottles. The companies that produce these products are similarly diverse. A handful of large additive companies employ hundreds of people dedicated to developing fuel and lubricant additives, while other companies consist of a few individuals striving to make one product successful, or one product might be marketed under multiple brand names.

Classification of Additives

Classifying additives is helpful in identifying those that are useful and relevant to utilities in Alaska. This study classifies additives based on the fuel property they address and their intended customer. "Aftermarket" additives are intended for fuel consumers: they are purchased and blended with the fuel by the final customer, after the fuel is purchased. Conversely, "before-market" additives are purchased by fuel producers and distributors. They are blended with fuel either at the refinery or by the distribution company that transports the fuel, and included in the price of the purchased fuel. By definition, Alaska utilities do not directly purchase before- market, bulk fuel additives, although they do benefit from their use. They should be aware of these products in order to inform their decisions about aftermarket products.

We identified 11 distinct additive classes that purport to improve different fuel properties in Table 2. Most classes only include aftermarket additives. However, some classes (pour point depressants and lubricity improvers) are included in both aftermarket and before-market products. There is only one additive class—conductivity improver—that is used as a before-market product exclusively. The attributes and risks of using a product from each of these classes are discussed further below.

Diesel Fuel Additive Descriptions and their Uses

This section reviews published papers and national laboratory tests to provide a technical understanding of fuel additives. Each additive type is defined, motivations for and risks of using a particular type of additive are given, as are the basic mechanisms that allow the additives to function. Understanding how the additives affect fuel properties and the mechanisms through which they act will help utilities recognize which additives they can use productively.

Pour Point Depressants

Diesel No. 2 is the standard diesel fuel in most climates. However, as distilled, No. 2 diesel begins to produce wax crystals that clog fuel filters at around 10°F, much too warm for most Alaska utilities. There are two basic solutions to this problem: the first is burning No. 1, rather than No. 2 diesel, or blending the two fuel grades together. Diesel No. 1 fuel sold in Alaska can be used at temperatures as low as -60°F, so it naturally satisfies utilities' requirements.

However, there is often an economic incentive to use No. 2 diesel rather than No. 1 due to the price per Btu of the two fuel types. The heat content per gallon is generally less for No. 1 than No. 2, although the exact difference is not specified by any national fuel standard and varies between different fuel sources. Chevron reports that their No. 2 fuel typically has an energy density a few percent higher than their No. 1 fuel, while the EPA reports that the difference is typically less than one half of a percent [3, 6]. Although the wholesale cost of No. 2 fuel tends to be less than the wholesale cost of No. 1 nationally [7], utilities report that the price differential is often negligible in Alaska. Utilities must learn the Btu content of their fuel and the price differential between No. 1 and No. 2 diesel at their particular location in order to determine whether a pour point depressant could be economical for them.

Rather than use No. 1 diesel, some utilities use a cold flow improver additive with their fuel. These additives typically work by changing the size and shape of wax crystals in the fuel so that it flows more easily even at low temperatures [8, 9].

Pour point depressants are the most common type of cold flow improver used in Alaska. Pour point refers to the temperature at which fuel no longer flows. Specifically, pour point is determined by observing the behavior of a sample of the fuel in a glass jar as it is cooled. The highest temperature at which the fuel does not move when the jar is turned horizontal is the pour point [10]. If the fuel temperature is below the pour point, it will not flow from the bulk fuel storage tanks.

The essential component of pour point depressants is a chemical that reacts with wax crystals and prevents them from growing. This reaction is most effective when the polymers in the pour point depressant are similar to the polymers in the diesel fuel [11]. However, the chemical structure of the hydrocarbons in diesel fuel is not regulated and varies dramatically between different crude oil sources. As a result, the efficacy of a particular pour point depressant depends on the fuel it is blended with [12-14]. It is not possible to specify how well any particular pour point depressant will work with all fuels.

Since the efficacy of pour point depressants depends on the crude oil source, refineries are the best sources of pour point suppressed fuel. Indeed, in the lower 48 refineries use pour point depressants to produce winter fuel on a regular basis [15]. In addition, a less expensive pour point additive can be used if blended with hot fuel at the refinery.

However, sometimes utilities in Alaska receive fuel and then realize that it does not have a sufficiently low pour point. In that case, utilities do not have the option of purchasing a specially designed additive, or blending the additive with the fuel while the fuel is hot. In that case, an aftermarket additive may help prevent fuel gelling. However, utilities must keep in mind that it will not be as effective as an additive designed for their crude oil source, and it may be difficult to adequately blend with the fuel.

Alternative Cold Flow Improvers

Several measurements besides pour point are also used to characterize low temperature fuel properties. These include the Cloud Point, Cold Filter Plugging Point (CFPP), and Low Temperature Flow Test (LTFT). Each fuel property provides some indication of how the fuel will perform in engines at low temperatures, but none fully describe cold weather performance [16]. Each measurement consists of one temperature characteristic of the fuel. The cloud point is the highest of these temperatures. It is the temperature at which the first visible wax crystals begin to form in the fuel as it is cooled [17]. Fuel at temperatures just below the cloud point may clog the fine one micron fuel filters used immediately before the fuel enters the engine, but can pass through coarse filters.

The CFPP and LTFT are defined as the temperature at which a specified quantity of fuel cannot be pumped through the filter assembly in less than sixty seconds. The differences between the two tests lie in the details of the pumping mechanism and the type of filter used in the assembly [18, 19].The temperature measured with both techniques is somewhere between the cloud and pour points. This report focuses on additives that target the pour point of fuels rather than the cloud point, CFPP or LTFT, because it is the most common type of cold flow improver in Alaska. Typically, utilities heat the diesel fuel as it enters the power plant, elevating the fuel above the cloud point—so it is important for the fuel to flow into the plant, but any wax crystals are dissolved by heating.

Conductivity Improvers

Due to new EPA regulations, the U.S. is in the process of switching to Ultra Low Sulfur Diesel (ULSD) for off-road diesel engines. ULSD contains less than 15 ppm sulfur (unregulated diesel fuel is often near 5,000 ppm sulfur). ULSD greatly improves exhaust emissions, but removing the sulfur from petro-diesel also results in a loss of lubricity and conductivity of the fuel. Therefore, conductivity and lubricity additives are necessary in ULSD, and unnecessary in diesel that has higher sulfur content. Refiners and suppliers (who are concerned with static discharge during fuel handling) blend these additives into the fuel, and preclude any need for utilities to be concerned with conductivity improvers. However, since they are present in ULSD fuel, they warrant a brief description.

Conductivity describes how easily electric charge can flow through the fuel. If fuel conductivity is too low, electric charge can accumulate while the fuel is transported, increasing the risk of a spark igniting the fuel. ASTM provides a minimum conductivity specification of 25 pS/m (pico-Siemens per meter) [16]. Satisfying the ASTM requirement requires a very small amount of additive, typically one or two parts per million of additive in ULSD.

Lubricity Additives

As the name implies, lubricity measures a fuel's ability to lubricate components in the fuel system. This property is particularly important for fuel injectors and pumps, which wear out quickly if fuel lubricity is too low [20]. Fuels with high sulfur content generally have sufficient natural lubricity to reduce wear in the engine. However, ULSD does not have adequate lubricity (sometimes referred to as "dry fuel"), necessitating the use of lubricity additives.

ASTM International standardized diesel lubricity measurement in 2005 with the High Frequency Reciprocating Rig (HFRR) Test [21]. In this test, a steel ball is rubbed against a disk while submerged in fuel for 75 minutes. At the end of the test, the size of the resulting wear scar on the disk is measured, and fuel lubricity is recorded as the size of the scar.

The ASTM lubricity standard for both No. 1 and No. 2 diesel fuels is a wear scar of 520 microns, as measured using the HFRR test [16]. John Deere, Detroit Diesel, Cummins and Caterpillar have their own lubricity specifications that range from 450 to 520 microns [22-25] (note—scuff ball tests are like golf—a smaller wear scar is a more stringent criteria). It is important to be aware that the HFRR test is only accurate to within 80 microns. Therefore, all of the engine manufacturers' lubricity standards are consistent with the ASTM standard to within the margin of error associated with the HFRR test [21].

All engine manufacturers suggest using a lubricity additive if the available fuel does not meet the lubricity standard (although they encourage consulting with your fuel supplier to make sure that the fuel is treated effectively). Most major engine manufacturers produce their own additives that include a lubricity component, and these are the only additives that engine manufacturers guarantee will not harm the engine. Using other additives generally will not void the warranty, but any damage that they cause will not be covered.

ASTM International only recently included a lubricity standard in their diesel fuel specifications to address problems with low lubricity ULSD. Untreated ULSD fuel does not meet the ASTM lubricity standard (let alone the more demanding engine manufacturers' standards). Therefore, most fuel suppliers blend a lubricity additive into the fuel after the sulfur has been removed but before the fuel is distributed.

If a lubricity additive is needed, products exist that are well understood and have been thoroughly tested (see Southwest Research Laboratory [26], for example). Unlike engine oil, diesel fuel and diesel fuel additives are primarily boundary lubricants: molecules in the fuel with polar 'heads' and nonpolar hydrocarbon 'tails' bond to the surface of the surrounding metal and create a protective layer on the surface of the metal [27, 28]. The types of molecules that can be adsorbed by metal and do not degrade fuel quality are useful for many applications, including cold flow improvers and corrosion inhibitors. As a result many additives that are intended for a different purpose improve lubricity as well [29]. Typically, additives in adequate concentration can achieve wear scars near 350 microns in the HFRR test (Figure 2). At that point, the additive concentration is sufficient to completely maintain a protective film on metal surfaces, and increasing the additive concentration does not improve the fuel lubricity further [29].

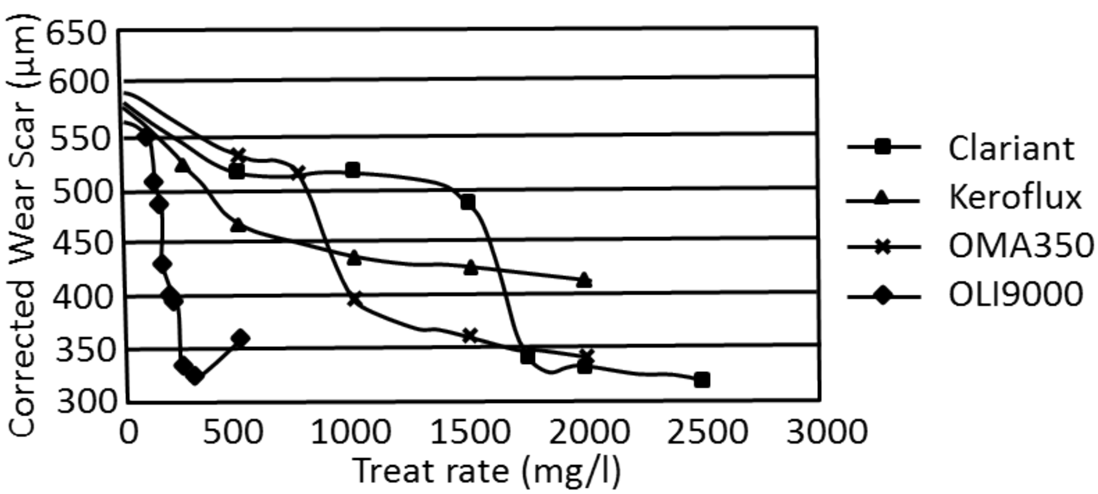

Figure 2. Documentation of the effect of various additives on fuel lubricity. Wear scar is corrected for humidity. Reproduced with permission from [29].

Thanks to the recent widespread use of lubricity additives and associated research, there is little risk associated with using one. Lubricity additives should be registered by the EPA to ensure that they do not introduce new pollutants to the fuel. Utilities considering an aftermarket additive should check with their fuel supplier to learn if a lubricity additive is already included in the fuel they receive, and if blending an aftermarket product with the fuel will improve the lubricity any further.

Fuel is often distributed by barges in Alaska, which transport different grades of fuel on different shipments. Jet fuel intended for use in aviation is the highest grade of fuel, and demands very tight water management procedures. The lubricity agents used in ULSD fuels are "hygroscopic" meaning that they are especially prone to capturing water from the air, so tanks that contain ULSD fuels treated with these compounds tend to accumulate more water than tanks that contain jet fuel (which does not need a lubricity additive). A tank used to move treated ULSD can be used for transporting jet fuel only after being subjected to a rigorous and expensive cleaning process. Barge transporters typically deal with this issue by transporting ULSD without the lubricity additive, and mix the additive in at the dock when fuel is delivered to the customer, metering it into the fuel while it is being transferred.

Utilities need to be aware that if a barge operator offers to blend a lubricity additive to their fuel during offloading, they should verify that the ULSD on the barge has not been treated with the lubricity additive, and accept this additive. There should not be an additional charge for this additive, as it is required to bring the fuel into ASTM D975 specifications.

Biocides

Microbial growth in fuel tanks, especially in bulk storage tanks with a layer of water on the bottom, is a well-known cause of fuel filter plugging and increased engine maintenance. Bacterial growth also can result in the production of acid environments that rapidly corrode steel storage tanks. Biocides are additives that can be used to treat and prevent biological growth.

Bacteria, yeasts, and fungi all grow in diesel fuel tanks [30]. Fuel is sterilized during the refining process by the high temperatures, but there are many opportunities for it to be contaminated during transportation and storage. Bacteria, yeast and fungi enter the fuel system through air vents and remain in fuel tanks and lines as fuel passes by. Inevitably, some biological organisms make it into all fuel tanks but their population rarely grows enough to affect engine performance.

When microbes do rapidly reproduce and accumulate in a fuel tank, it creates a major problem. Fuel filters will be clogged frequently with goo and fuel injectors can be blocked with insoluble organic matter created by the microbes. In this case, the fuel tank must be treated with a biocide, all of the fuel thoroughly filtered, and the tank cleaned. Skipping any of these steps invites a second population of contaminates to grow from surviving organisms.

Maintaining fuel stocks by minimizing their water content is the best way to prevent biological growth [31]. Generally, microbes need water to live and multiply, so periodically draining water out of fuel tanks can dramatically reduce the threat of biological growth.

Most utility managers in Alaska reported draining their tanks approximately once per year, or not at all. However, in warmer climates companies are known to drain their fuel tanks every 15 days [30]. Given that only two utilities reported having trouble with biological growth in their tanks, it appears that draining water from tanks once per year is sufficient in Alaska.

When fuel is found to be contaminated with biological growth, biocides are an important part of treatment [32]. The efficacy of biocides has been studied and published in peer reviewed articles, and their use is widely accepted in the industry [30, 31]. However, the effectiveness of a particular chemical depends on the specific type of microbe growing in the fuel tank. As a result, it may be difficult for utilities to identify the most effective additive if they have a biological growth in their tank.

Fortunately, some general principles apply to purchasing biocides that give a high probability, if not certainty, of success. In order to treat a contaminated tank, a biocide that is soluble in both water and fuel should be used. Biocides that are only soluble in fuel are used by refineries or distributors to ensure they deliver quality fuel. Other biocide additives that are soluble in only water are used to prevent biological growth in the water in contaminated fuel tanks without purchasing enough additive to treat the whole tank. Since once a microbe has established a strong population in the tank it will be dispersed throughout the fuel system, it is prudent to treat the whole system to kill all of the biological growth.

Biocides can adversely affect fuel systems if biomass is growing on the walls of fuel tanks. In that case, the biocides can kill the biomass, causing it to detach from the walls and become entrained in the fuel. This slug of non-oil material can be quite massive and thereby extensively clog fuel supply to the engine. Therefore, a complete treatment for biological contamination should involve four steps: drain all water from the system, treat the entire system with a biocide, filter all fuel (preferably into a clean tank) before use in a diesel engine, and clean the contaminated tank.

Fuel Stabilizers

Fuel stability measures a fuel's tendency to form resins, gums, or other insoluble products before it is combusted. The processes that form insolubles are highly temperature dependent, which creates two distinct stability challenges. Many modern engines cool fuel injectors with fuel, exposing fuel to high temperatures before it is burnt in the engine. Fuel with good "thermal stability" must not degrade when exposed to elevated temperatures for hours before combustion. At outdoor air temperatures, fuel stability typically does not become an issue for many months or years. Fuel with good "storage stability" is essential for many military applications that require storing fuel for years before use [33].

Stabilizer additives can be used to improve the stability of diesel fuel for long-term storage (over one year) [34]. There are several types of additives that address different mechanisms of instability. The most common stabilizers contain antioxidants that bond with free radicals in the fuel to prevent them from initiating unwanted reactions [35]. Other additives known as metal deactivators prevent reactions between fuel and metals that may be present in fuel lines or tanks [33]. The military requires fuels that may be stored over six months to include a stability additive [36].

The thermal stability of diesel fuel generally is not regulated, and can vary significantly between fuels. This makes it difficult to determine whether a stability additive is necessary. However, ASTM does provide a "Standard Test Method for High Temperature Stability of Middle Distillate Fuels" [34]. According to the National Conference of Weights and Measure, fuel labeled "premium diesel" must meet a minimum thermal stability requirement, as measured by the ASTM test [37].

Given that many rural Alaska utilities store fuel for a year between deliveries, it may seem that they should use a stability additive. Indeed, some refiners recommend using a stability additive if fuel will be stored for over a year [13, 15]. However, no utilities reported any trouble with clogging filters or engine problems traceable to long-term storage of diesel fuel. This may be attributable to the low temperatures in rural Alaska. ASTM's *Fuels and Lubricants Handbook* reports that the rate at which diesel fuel decomposes typically falls by a factor of two for every 10°C decrease in temperature [38]. That implies that fuel is roughly 16 times more stable at -20°F than it is at 60°F.

The one exception to the rule above is the attempt to use fish oil bio-diesel in Alaska; this fuel proved to be quite susceptible to oxidation, and proved to be only partially stabilized by use of a food grade anti-oxidant. Raw fish oil is less prone to this problem than fish oil that has been treated to remove glycerides, and raw fish oil is being used successfully by some fish processing plants.

Cetane Enhancers

Cetane number describes the ignition quality of diesel fuel. It is measured by comparing the ignition delay of a fuel to the ignition delay of two reference chemicals (cetane and heptamethyl nonane or HMN). Ignition delay is the length of time between when fuel is injected into the combustion chamber and when the fuel ignites. Cetane ignites very quickly and is given a cetane number of 100, while HMN has a longer ignition delay and is given a value of 15. In the U.S., diesel fuel typically has a cetane number a little greater than 40, as required by ASTM D975.

The cetane number of fuels can be raised by 5 to 10 points with the addition of an additive. Ethylhexyl nitrate is perhaps the most well-known cetane-improving chemical, but numerous other chemicals can be used as well [39-41]. Cetane number is primarily important in cold start applications [25]. There is also some interest in using cetane enhancers to improve engine performance, but there is little evidence to support this [42]. In fact, using diesel with too high a cetane number can adversely affect engine performance [43]. In diesel power plants, there is little need for cetane boosters since the engines are kept indoors and rarely cold started.

Injector Cleaners

It is well known that deposits can form within the fuel system of diesel engines. Deposits on the fuel injectors (Figure 3) are of particular importance. These deposits can restrict fuel flow, decreasing the atomization of the fuel stream and also reducing the homogeneity of the fuel air mix in the combustion chamber [44]. This leads to an increase in hazardous emissions as well as a decrease in fuel efficiency.

Injector deposits are an agglomeration of carbon and hydrocarbon molecules known as coke, as well as partially oxidized fuel molecules and trace amounts of zinc or other metals dissolved in the fuel [44, 45]. Their effects are particularly noticeable in modern engines that produce minimal emissions and rely on small diameter injector nozzles. Deposits are difficult to avoid in diesel engines, although the rate at which they form varies significantly depending on fuel and engine type. Hydrocarbon molecules can form the base of the deposits and provide a sticky surface for particles to bond with [45]. Once the deposits begin to form, carbon, more HCs and trace quantities of metals or other contaminates collect in the deposits.

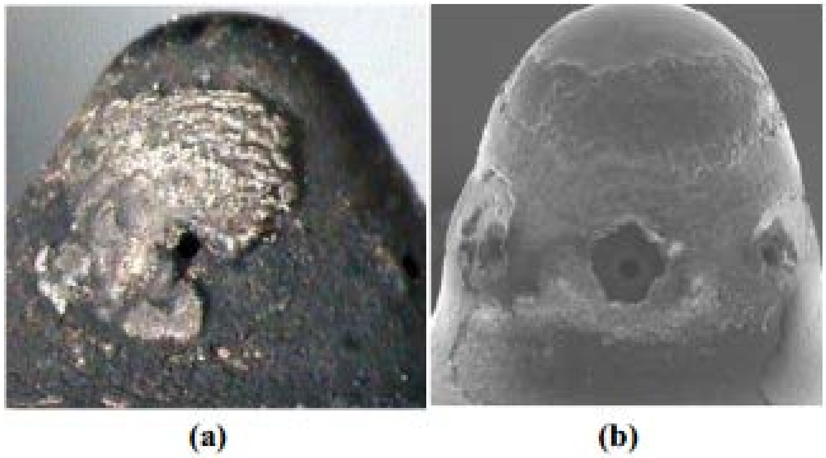

Figure 3. Deposits on fuel injector tips. Image from [1].

The EPA requires all gasoline in the U.S. to contain a detergent, but there is no similar requirement for diesel fuel [46]. As a result, detergent additives are not typically included in diesel fuel by refineries [15, 47, 48]. Nonetheless, tests have shown that diesel detergents can remove deposits and thereby improve engine performance (e.g., [49]). Therefore, it is reasonable to use an injector cleaner additive in older engines that may have unwanted deposits accumulated on their fuel injectors. Typical symptoms of injector deposits include a loss of power and black smoke in the exhaust [50]. A variation in cylinder temperature as the engine ages may also be used as an indication of deposit formation in engines with advanced instrumentation [51]. Several factors affect the rate at which deposits form: fuel sulfur content, trace concentrations of metals in the fuel, and operating temperature of the engine are a few important examples. These variables make it difficult to predict when an injector cleaner will be needed.

Water Emulsifier/De-emulsifier

Some water should be expected in diesel fuel. Although the refining process evaporates all of the water out of the fuel, diesel is inevitably contaminated as it is transferred to barges, transported over sea or land, and stored in ventilated fuel tanks. Engine manufacturers have learned to cope with water-contaminated fuel by using water separating filters and allowing some water to simply pass through the engine. Some diesel engine manufacturers provide a maximum permissible water content for their engines' fuel, and these acknowledge that fuel contaminated with water is acceptable, as long as the concentration is below their standard. Caterpillar, for instance, recommends fuel with less than .05% water content by weight [25]. In order to keep the water content of fuel sufficiently low, it is good practice to drain the water from the bottom of fuel tanks periodically. Most utilities in Alaska that reported draining their tanks did so once per year.

Despite the best fuel maintenance practices and engine designs, enough water can occasionally accumulate in fuel to damage the engine or affect performance. Three utilities in Alaska reported having experienced problems due to water in their fuel. Their solutions varied: AVEC reported circulating the fuel through filters and retrofitting tanks with valves that allow them to drain the water from the bottom of their tanks [52], while Aniak Light and Power blended an additive into their fuel (Aniak LNP was uncertain of the efficacy of the additive) [53].

There are two types of additives meant to treat water-contaminated fuel: emulsifiers and de-emulsifiers. Emulsifiers distribute water throughout the fuel in an emulsion. This prevents large droplets of water from entering the engine at once, and allows the water to be slowly consumed by the engine. De-emulsifiers have the opposite effect: they cause water that is in an emulsion with the fuel to settle to the bottom of the fuel tank where it can be drained.

Generally, engine manufacturers recommend using water-separating filters to deal with contaminated fuel. Cummins specifically recommends against using water emulsifiers, as they impede the effectiveness of water separators [24]. Conversely, water de-emulsifiers cause water to separate from fuel chemically, and may improve the efficacy of water separating filters. Use of methanol (the standard way of treating water and ice in gasoline engines) is not recommended in diesel fuels.

Additives to Reduce Emissions

In ideal combustion of petroleum products, hydrocarbons react with oxygen to produce water and carbon dioxide. In reality, combustion is dirtier. There are four pollutants of particular concern: carbon monoxide (CO), unburned hydrocarbons (HC), particulate matter (PM) and oxides of nitrogen (NO_x). A brief understanding of the primary mechanisms that produce these pollutants is essential to evaluating additives.

Carbon monoxide forms when hydrocarbons are burned with insufficient oxygen. Therefore, the most important factor in minimizing CO production is the air-fuel ratio in the combustion chamber. Some CO is also formed at the high combustion temperatures of internal combustion engines when CO_2 dissociates into CO and O_2, but this source is of secondary importance [54].

Unburned hydrocarbons in the engine exhaust results from "quench zones" in the combustion chamber. Quench zones are small low temperature regions that occur near the cylinder walls or regions where fuel accumulates to create a locally fuel rich equivalence ratio [55]. In these zones, the fuel does not burn completely, leaving unburned HC molecules in the exhaust gas. Secondary mechanisms for HC emissions include temporary absorption of the HC by lubricating oils or carbon deposits, and liquid fuel films that may occur on combustion chamber walls [54, 55].

Particulate matter (PM) includes all emissions that can be collected with a filter paper. A variety of substances make up the particles, but the most significant fractions are carbon, sulfates, and unburned engine oil. Low sulfur fuels, of course, limit the number of sulfate particulates diesel engines emit, and the use of ULSD results in lower PM emissions. Engine oil containing sulfur that enters the combustion chamber often burns partially, producing PM emissions. Typically, particulate pollutants consist of a hard elemental carbon core, surrounded by layers of unburned hydrocarbons, sulfuric acid and a metals/oil residue, as shown in Figure 4.

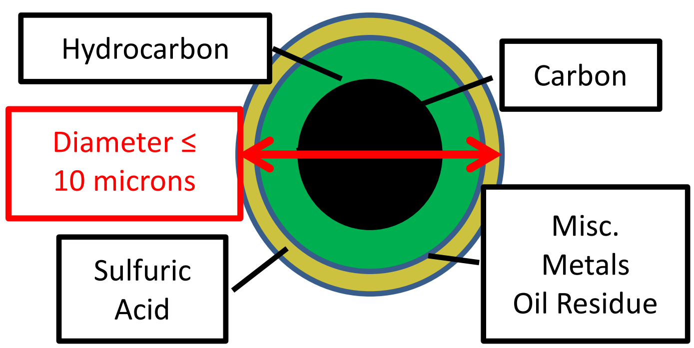

Figure 4. Illustration of an example diesel engine particulate. Reproduced with permission from [107].

Nitrogen oxide emissions are different from the other pollutants because they do not contain any elements from the fuel. Nitrogen oxide forms when nitrogen and oxygen molecules in the air react with each other. At normal atmospheric temperatures, nitrogen and oxygen molecules remain separate. However, at the high temperatures found in the combustion chamber NO_x forms quickly and remains in the exhaust after it has cooled. The temperature of combustion is the primary factor in determining how much NO_x is produced [54]. Modern electronic injection engines control NO_x by carefully metering fuel into the cylinder at specific points in the compression curve to limit the maximum temperatures reached in the combustion event. (It is not clear how any fuel additive would reduce NO_x, as its formation is governed by management of fuel injection timing, and is independent of fuel composition.)

Only a small fraction of the fuel ends up as any of these pollutants. Tier 1 EPA standards (which have been in effect for non-road diesel engines since 1996 and do not include exhaust aftertreatment devices) set the maximum emissions of HC, NO_x, PM and CO at 1.3, 9.2, .54 and 11.4 g/kWh, respectively. These standards effectively require less than 0.6 % of fuel to be exhausted as unburned hydrocarbons and less than 0.25% of fuel (by mass) to be released as particulate matter[56]. It is this small fraction of fuel that produces hazardous exhaust products that emissions additives must address.

Since the introduction of Tier 1 standards, the EPA has progressively introduced new, stricter regulations. Today, the EPA is beginning to enforce the transition to the fourth and final set of off-road diesel emission standards. Under Tier 4 standards, the regulated emissions are reduced to .19 (non-methane HC), .4 (NO_x), .02 (PM) and 3.5 (CO) g/kWh. This is a reduction in HC emissions by a factor of six, NO_x and PM by a factor of 20, and CO by a factor of three. The most effective technology for reducing these emissions is exhaust aftertreatment. The use of these devices, which require ULSD, makes the EPA tier 4 standards possible. The tier four standards first began to take effect in 2011 and will be phased in through 2015 (see Table 3 for more detail). There is little interest in emissions additives for engines with exhaust aftertreatment devices, as the effectiveness of the catalytic surfaces may be affected by the use of additives. Most diesel gensets in current use in Alaska power plants are grandfathered under less strict EPA standards and do not have aftertreatment devices. Some additives are marketed that claim to reduce emissions in these engines.

Combustion catalysts constitute a large class of diesel additives that claim to reduce emissions and improve fuel economy. They typically include an oxidation catalyst, often platinum, that is blended into the fuel or airstream as part of an organometallic molecule, or inserted into the fuel line in a solid form immediately before the combustion chamber. The element is then born by the fuel into the combustion chamber, where it is claimed to lower the combustion temperature, thereby reducing NO_x emissions, and simultaneously reducing the amount of hydrocarbons that remain unburned. The EPA stopped registering new additives that contained metal elements in 2008 due to a new interpretation of a “substantially similar” clause in the EPA’s fuel additive registration regulations [57, 58]. Nonetheless, many metal catalyst additives garner significant interest and are grandfathered into the system, and are still being actively marketed.

Several studies have observed reduced emissions and improved engine performance using a combustion catalyst additive or device; see [59-61]. Each of these papers report on experiments that involved running an engine at a set load with both untreated fuel and fuel blended with a metal additive. Kelso et. al. (1990) tested three different engines with a platinum-based fuel additive, and reported reductions of 6-46% in CO emissions, and 12-42% in HC emissions. The broad range is not explained, and there is no analysis of the statistical significance of these results. NO_x emissions appeared to increase by approximately 3%. Epperly (who co-authored the paper) filed a patent for this additive the year before publishing the paper, and was awarded the patent in 1991 [62]. Okuda et al. tested one engine (a 3116 Caterpillar without exhaust gas recirculation or aftertreatment) with a platinum-cerium additive. The paper focused exclusively on particulate emissions and reported a 34% reduction in PM emissions at a treat rate of .13 ppm platinum, 7.5. The study also measured what fraction of the platinum exited the engine through the exhaust, and found that 85% of the platinum remains in the engine. Additives like these that leave a deposit in the combustion chamber are explicitly forbidden by engine manufacturers, due to concern about the effect on long-term wear in the engine.

There are also many studies that report that metal catalysts have no significant effect on emissions; see [63-66]. The papers by Thring and Siegla and Plee both report on experiments with “catalytic engines.” These engines have a platinum lining inside the combustion chamber. Thring reports an improvement in HC emissions using the catalytic engine, but an increase in CO emissions and inconsistent results for NO_x emissions, depending on the engine load. Siegla and Plee conducted an experiment in which they collected baseline emissions data on a diesel engine, then disassembled the engine, coated the combustion chamber with platinum, and reassembled the engine. They reported no significant changes in emissions, noting that some variation should be expected due to their re-assembly of the engine. Du et al. tested a ferrocene additive by collecting baseline data with standard number two diesel, and then running the engine with treated diesel for 800 hours while monitoring NO_x emissions and fuel economy. There was no trend in the NO_x emissions from the engine. The most striking feature of their NO_x measurements is their variability from day to day: NO_x emissions varied by 15% while fluctuating above and below the mean throughout the test.

A very strongly worded EPA evaluation was found for a metal catalyst retrofit device known as "Gasaver." The evaluation was requested by the FTC due to allegations of false advertising. The device was designed for gasoline engines, but used a principle similar to many products available on the market today and of interest to Alaska utilities. In the Gasaver, air is bubbled through a liquid "platinum concentrate," and then pumped into the crankcase, supposedly resulting in reduced emissions and improved efficiency. In the EPA test, three different vehicles accumulated 2,000 miles with and without the device. Although emissions varied by 10 to 20 % between tests, there was no reduction in any of the measured pollutants that was consistent in all three vehicles. The EPA concluded, "The Platinum Gasaver has no emission or fuel economy benefit" [66]. This does not necessarily prove that the Gasaver would not work on a different engine, or that other platinum additives will not reduce emissions on diesel engines. However, it does demonstrate that not all engines respond to the purported benefits of retrofit devices that may claim to produce dramatic efficiency improvements, and that such claims should be treated with skepticism.

It must be noted that the literature cited above is all based on older engine designs. The EPA has been very concerned about reducing emissions from diesel engines, but has used the development of new injection systems and exhaust aftertreatment systems, combined with the use of ULSD fuels, to achieve its goals. It is not clear that any additive could achieve similar reductions in emissions, or that use of these products can provide any additional emissions benefits.

Efficiency

Although typically less than 40% of the energy in diesel fuel is converted to electricity in diesel generator sets (or gensets), there is limited room for improvement in diesel engine efficiency that can be achieved by modifying the fuel. This is due to the thermodynamic limit to the efficiency of the diesel cycle, losses due to friction in the engine, and inefficiency of the electric generator. Estimating the amount of energy that is left for the engine to produce electricity based on these limiting factors provides some context for the potential impact of fuel additives.

Even with the outstanding improvements in diesel engine technology afforded by electronic control systems and by adapting fuel injection to changing engine conditions, the overall efficiency of diesel combustion cycles is limited by thermodynamics. This much-studied subject of compression combustion shows that the theoretical maximum ability to convert the chemical energy of a fuel into work in an ideal compression combustion cycle is limited to around 60% [67]. The exact limit depends upon properties of the engine itself (e.g., compression ratio of the engine and when in the cycle the exhaust is expelled in relation to the completion of combustion) rather than the fuel. For non-ideal compression combustion in a relatively small diesel engine, the efficiency is limited to less than 40% primarily due to irreversible processes in the combustion [68].

Today in Alaska's utilities, efficiencies on the order of 15 KWh/gallon have been reported for utilities using relatively large engines running on available commercial diesel fuels. This represents an overall thermal efficiency of about 37%. Since the electrical generator itself is nominally 90% efficient (depending upon load) due to its mechanical losses, these diesel engines appear to be run very near their maximum possible efficiency. Smaller engines tend to be less efficient: in Alaska utilities smaller diesel engines are generally reported to be in the range of 12 to 14 kwh/gallon, corresponding to 30 to 35% overall thermal efficiency if they are running on No. 2 diesel.

Lower efficiencies are realized for all engines running at low loads and for smaller versus larger engines. These factors are important considerations in electrical utility powerhouse design and operation.

It seems obvious that much more energy could be used by extracting heat energy from the exhaust, where about 40% of the diesel fuel energy ends up. An additional 20% of the diesel fuel energy ends up heating the engine cooling water. Utilizing diesel gensets as combined heat and power plants has the potential to improve the system efficiency much more than fuel additives could. In the early 1980s, many plants incorporated recovered heat to schools or other facilities when relative fuel prices increased. As fuel prices decreased in the mid-1980s, several of those systems fell into disrepair. With fuel price increases of nearly 300% in the past ten years, such systems are now being repaired or newly designed. Partnerships between power plant owners and heat users such as water and sewer systems, schools and other facilities are increasing. Worth noting also is that the new low sulfur fuels emit less particulates and less sulfur-containing compounds (high sulfur fuels result in a high sulfuric acid dew point, resulting in rapid corrosion of exhaust stacks—new fuels don't have this problem), allowing for better heat recovery systems.

Efficiency Increasing Additives and Devices

In the past, many consumers were convinced to purchase fuel-saving devices by misleading advertisements. As a result, the Federal Trade Commission (FTC) has worked with the EPA to develop an evaluation program for efficiency and emissions additives and retrofit devices, especially those used in transportation applications. In the program, the EPA administrator and the FTC have the power to require a test for any additive or retrofit device. Companies can also apply to have their product tested. The device must be tested in an independent laboratory first, and if the results demonstrate a statistically significant improvement, the EPA may conduct confirmatory testing at the company's expense [69]. Based on these evaluations, the FTC advises consumers to be cautious: "It's a smart idea to be skeptical of any gas-saving claims for automotive devices or oil and gas additives" [70]. The EPA has evaluated over 90 additives and retrofit devices, but has found none that significantly affect fuel efficiency [70].

Magnetic Fuel Conditioners

Magnetic fuel conditioners are a type of retrofit device that has been tested by the EPA as well as two utilities in Alaska. These devices, which consist of a magnet mounted somewhere along the fuel line, are claimed by the manufacturer to make the fuel more volatile or otherwise improve its combustion properties (e.g., [71]). The EPA tested one of these products called Super-Mag in 1982 that claimed to improve gasoline engine efficiency by up to 30 percent. The EPA used the standard Highway Fuel Economy Test and the Federal Test Procedure to measure the efficiency of three vehicles with and without the device [72]. The study observed no significant change in the efficiency or emissions of any of the vehicles [73]. Similarly, neither of the Alaska utilities that tested magnetic fuel conditioners observed any significant change in engine efficiency [51, 74].

Combustion Catalysts

Combustion catalysts (already discussed in the emissions section), also commonly claim to improve engine efficiency by reducing the amount of unburned fuel passing through the engine and improving the "quality of combustion." There are some claims of efficiency improvements due to combustion catalysts: Kelso et al. reported a 5% efficiency improvement using their platinum based additive, and a test of a metal catalyst product by the Southwest Research Institute (SRI) reported a 2% improvement using an inline fuel catalyst [59, 75]. In the SRI test, a heavy-duty Cummins Diesel engine was run for 125 hours with and without the device, and Brake Specific Fuel Consumption was estimated based on the amount of CO_2 emitted from the exhaust. The test was requested and paid for by the device manufacturer. (Worth noting is that a 2% change on a single engine run for 125 hours would not be considered statistically significant under the EPA/FTC criteria.)

Two Alaska utilities reported apparent efficiency improvements when testing a combination of catalyst retrofit devices or additives. However, neither utility has installed these means of supposed efficiency improvement on their newest engines.

One diesel engine manufacturer, Cummins, markets a fuel additive that contains platinum (Platinum Plus DFX), that it claims will enhance fuel economy [24]. However, Cummins goes on to state in the same document, "There are no known additives that increase the power or improve the efficiency of a properly maintained engine."

Despite the collection of supposedly positive test results available, there are strong recommendations against using metal catalysts as efficiency improvers. In Caterpillar's engine fluid recommendations, for instance: "Metallic fuel additives can cause fuel system/injector fouling and aftertreatment device fouling. Caterpillar discourages the use of metallic fuel additives in most applications" [25].

As previously mentioned, the EPA no longer registers additives that include metals since they produce ash and can contaminate exhaust treatment systems. The U.S. Transportation Research Board also critiqued metal additives as early as 1984, noting that "tests [of metal catalysts] have generally indicated failure or, at best, marginal success [with the exception of the limited success of barium and manganese smoke suppressant additives]" [43]. These critiques are supported by EPA tests of several combustion catalyst additives and retrofit devices [66, 76, 77].

Older Versus Newer Engines

Older diesel engines, from the 1970's and before, were notorious for belching clouds of black particulates into the air, especially when the engines were being heavily loaded, but those engines are aging out of the current diesel engine fleet. Those engines also tended to have lower compression ratios and correspondingly low efficiencies in the low to mid 20% range.

In general, diesel engine efficiency has been improving over the past few decades, due to the improvements associated with electronic injection systems, which allow precise control of when fuel is injected into the engine, and improved turbochargers, which lead to higher, more efficient compression ratios. The newest Tier IV engines are slightly less efficient than Tier III engines. These losses are most likely due to the energy costs of after-combustion treatment of the exhaust, and changes in injection timing to prevent the high combustion temperatures associated with the formation of NO_x.

Well-Maintained Versus Less Well-Cared-for Engines

Engine manufacturers strongly advocate good maintenance practices, and urge special attention to the fuel injection system. Clearly, engine reliability and optimal performance can be better assured if the engine is well maintained. Additives intended to improve the efficiency of diesel engines have been demonstrated to have no observable effect on well-maintained engines. Use of additives to correct malfunction resulting from neglected maintenance of engines has anecdotal support, but has not been studied for this report.

EPA Emissions Guidelines

The EPA regulates four pollutants from compression ignition engines: unburned hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO). In 1996, the EPA initiated a tiered approach to emissions regulation. Under the tier system, engines must meet different emission standards based on their manufacture date and power rating. Initially, the EPA planned to have four distinct tiers that would be required for engines manufactured between 1996 and 2015. However, engine manufactures could not develop the technology to meet tier 4 standards quickly enough, motivating the EPA to introduce interim tier 4 standards in between the tier 3 and final tier 4 standards. The changes the EPA introduced to its tier standards, as well as the sheer number of regulations, can make the program confusing and frustrating for utilities. The regulations are summarized in Table 3, including the most recent EPA information (dated March 6, 2013).

As shown in Table 3, requirements for tier 1 and tier 4 engines differ significantly. By tier 4, the EPA requires a reduction of NO_x by a factor of 20, a reduction of PM by a factor of 15, and smaller reductions in CO and NMHC. The tier 1 through tier 3 standards have been met through improvements in electronically controlled fuel injectors and other modifications to the engines that do not require exhaust gas aftertreatment devices. However, in order to meet the tier 4 standards, engine manufacturers will need to install catalytic converters in their exhaust systems. Sulfur oxides quickly degrade these devices, making them impractical for fuels with too much sulfur. As a result, the EPA began requiring Ultra Low Sulfur Diesel (ULSD) for use in on-road diesel engines in 2007, and is phasing the fuel in for off-road engines between 2007 and 2014 [39].

Tier 4 engines with exhaust aftertreatment devices require ULSD. Over the past five years, the EPA has introduced regulations that have caused ULSD to be phased in to the U.S. fuel distribution system. In the contiguous 48 states, ULSD is now ubiquitous. However, there has been resistance to the new regulations in Alaska, because communities are concerned that the regulations raise the cost of fuel and necessitate storing two different types of fuel (which would require new fuel tanks in many cases). Due to the difficulty of delivering fuel to rural communities in Alaska, the EPA granted the state a more relaxed timeline for transitioning to ULSD than the rest of the country. Therefore, many utilities are not yet required to use ULSD. However, as ULSD becomes the norm in the lower 48 and other countries in the world, ULSD is sometimes less expensive and more available than higher sulfur content fuels, so some communities have begun using ULSD despite the EPA's leniency.

Table 3. EPA's exhaust emission standards for nonroad compression-ignition engines.

Rated Power	Tier	Model year	NMHC (g/kW-hr)	$NMHC+NO_x$ (g/kW-hr)	NO_x (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
kW<8	1	2000-2004	-	10.5	-	1.0	8.0
	2	2005-2007	-	7.5	-	0.80	8.0
	4	2008+	-	7.5	-	0.40[a]	8.0
8≤kW<19	1	2000-2004	-	9.5	-	0.80	6.6
	2	2005-2007	-	7.5	-	0.80	6.6
	4	2008+	-	7.5	-	0.40	6.6
19≤kW<37	1	1999-2003	-	9.5	-	0.80	5.5
	2	2004-2007	-	7.5	-	0.60	5.5
	4	2008-2012	-	7.5	-	0.30	5.5
		2013+	-	4.7	-	0.03	5.5
37≤kW<56	1	1998-2003	-	-	9.2	-	-
	2	2004-207	-	7.5	-	0.40	5.0
	3[b]	2008-2011	-	4.7	-	0.40	5.0
(Option 1)[c]	4	2008-2012	-	4.7	-	0.30	5.0
(Option 2)[c]	4	2012	-	4.7	-	0.03	5.0
	4	2013+	-	4.7	-	0.03	5.0
56≤kW<75	1	1998-2003	-	-	9.2	-	-
	2	2004-2007	-	7.5	-	0.40	5.0
	3	2008-2011	-	4.7	-	0.40	5.0
	4	2012-2013[d]	-	4.7	-	0.02	5.0
		2014+[e]	0.19	-	0.40	0.02	5.0
75≤kW<130	1	1997-2002	-	-	9.2	-	-
	2	2003-2006	-	6.6	-	0.30	5.0
	3	2007-2011	-	4.0	-	0.30	5.0
	4	2012-2013[d]	-	4.0	-	0.02	5.0
		2014+	0.19	-	0.40	0.02	5.0
130≤kW225	1	1996-2002	1.3[f]	-	9.2	0.54	11.4
	2	2003-2005	-	6.6	-	0.20	3.5
	3	2006-2010	-	4.0	-	0.20	3.5
	4	2011-2013[d]	-	4.0	-	0.02	3.5
		2014+[e]	0.19	-	0.40	0.02	3.5
560≤kW<900	1	2000-2005	1.3[f]	-	9.2	0.54	11.4
	2	2006-2010	-	6.4	-	0.20	3.5
	4	2011-2014	0.4	-	3.5	0.1	3.5
		2015+[e]	0.19	-	3.5[g]	0.04[h]	3.5
kW>900	1	2000-2005	1.3[f]	-	9.2	0.54	11.4
	2	2006-2010	-	6.4	-	0.20	3.5
	4	2011-2014	0.40	-	3.5[g]	0.10	3.5
		2015+[e]	0.19	-	3.5[g]	0.04[h]	3.5

Nonroad Compression-Ignition Engines – Exhaust Emission Standards. The table and footnotes are adapted from the EPA website, accessed on March 6, 2013 [78].

[a] Hand-startable air-cooled direct injection engines may optionally meet a PM standard of 0.60 g/kW-hr. These engines may optionally meet Tier 2 standards through the 2009 model years. In 2010, these engines are required to meet a PM standard of 0.60 g/kW-hr.

[b] These Tier 3 standards apply only to manufacturers selecting Tier 4 Option 2. Manufacturers selecting Tier 4 Option 1 will be meeting those standards in lieu of Tier 3 standards.

[c] A manufacturer may certify all their engines to either Option 1 or Option 2 sets of standards starting in the indicated model year. Manufacturers selecting Option 2 must meet Tier 3 standards in the 2008-2011 model years.
[d] These standards are phase-out standards. Not more than 50 percent of a manufacturer's engine production is allowed to meet these standards in each model year of the phase out period. Engines not meeting these standards must meet the final Tier 4 standards.
[e] These standards are phased in during the indicated years. At least 50 percent of a manufacturer's engine production must meet these standards during each year of the phase in. Engines not meeting these standards must meet the applicable phase-out standards.
[f] For Tier 1 engines the standard is for total hydrocarbons.
[g] The NO_x standard for generator sets is 0.67 g/kW-hr.
[h] The PM standard for generator sets is 0.03 g/kW-hr.

Similar to the design of the emission tiers, the year in which diesel engine operators must begin using ULSD depends on the size of the engine. In Alaska, the regulations are further segregated based on whether or not the generator is located in a rural community. Table 4 summarizes the ULSD requirements for Alaska, as published by the Alaska Department of Environmental Conservation [79]. Generally speaking, utilities are HAP (Hazardous Air Pollutant) area sources rather than major sources, since they emit less than ten tons per year of any regulated air pollutant [32]. Therefore, Table 4 shows that rural Alaska utilities are not required to use ULSD until they purchase engines from model year 2014 and newer. However, utilities on the road system are required to use ULSD if they have engines manufactured after April 1, 2006, and all mobile compression ignition engines are required to use ULSD.

Engine Manufacturer Statements on Fuel Additives

Caterpillar, Cummins, John Deere, and Detroit Diesel all hold similar positions on aftermarket additive use. They discourage using fuel additives in general, but acknowledge that Cetane boosters, lubricity improvers, detergents, and pour point depressants are necessary or useful in some circumstances [25, 24, 81, 23]. The following statement from Caterpillar's Machine Fluids Recommendations is representative of all of the engine manufacturers:

> *Caterpillar does not generally recommend the use of fuel additives. In special circumstances, Caterpillar recognizes the need for fuel additives. Fuel additives need to be used with caution … Consult your fuel supplier for those circumstances when fuel additives are required.* [25]

Sometimes statements by these manufacturers about their own products seem to contradict statements they make about aftermarket products in general. Here is a quote from the same Caterpillar document:

> *Cat Diesel Fuel Conditioner is a proven high performance, multipurpose diesel fuel conditioner … Cat Diesel Fuel Conditioner has been validated through lab and field tests to improve/reduce diesel fuel consumption and emissions for typical fleets through fuel system/injector cleanup, and to help maintain new engine performance by keeping fuel systems clean.*

Similar to the Cat Diesel Fuel Conditioner, Cummins promotes "Cummins Filtration Platinum Plus DFX Fuel Borne Catalyst " as an additive product that improves efficiency, while John Deere promotes "Fuel-Protect Diesel Fuel Conditioner" [24, 81]. While manufacturers release formal statements that advise consumers to only use additives in special circumstances, the same companies claim in advertising the products they produce that their additives will improve engine performance in typical trucking fleets or other applications. For example, Caterpillar states that "Average fuel economy benefits across typical fleets may be in the 2-3+% range" [25]. While manufacturers are skeptical of most additives, they make broad positive claims about their own.

In general, using a fuel additive will not automatically void engine warranties. However, any damage attributed to an additive will not be covered by the warranty [23]. Purchasing a fuel additive produced by the engine manufacturer avoids any potential for confusion on this issue, because the manufacturers all guarantee that their products will not adversely affect their engines. Manufacturers do not test additives produced by other companies, and refuse to condone or condemn the use of any specific products as a result.

Manufacturers do explicitly forbid the use of some types of additives. Cummins reports that fuel additives containing ash (incombustible material) cause deposits in the combustion chamber and clog particulate filters [24]. Detroit Diesel condemns the use of any additive containing fluoride, bromide, or chloride due to their corrosive properties, and also forbids additives that contain calcium, barium, zinc, phosphorous, sodium, magnesium, iron, copper, or manganese to prevent deposits in the combustion chamber [23]. Caterpillar provides a similar statement, stating that "Metallic fuel additives can cause fuel system/injector fouling and aftertreatment device fouling" [25].

Table 4. EPA Alaska diesel fuel requirements. Table reproduced from [79].

Current Alaska Diesel Fuel Requirements **June 12, 2012**

	Engine Size	Dates	FAHS[1]	Rural[2]	Regulation
STATIONARY SOURCES					
EXISTING	Stationary non-emergency CI engines <30 l/cyl[3], 300-500 HP at HAP major sources	Installed before 6/12/06	15 ppm	15 ppm	NESHAP Subpart ZZZZ
EXISTING	Stationary non-emergency CI engines <30 l/cyl, >500 HP at HAP major sources	Installed before 12/19/02	15 ppm	15 ppm	NESHAP Subpart ZZZZ
EXISTING	Stationary non-emergency CI engines <30 l/cyl, >300 HP at HAP area sources	Installed before 6/12/06	15 ppm	No requirements	NESHAP Subpart ZZZZ
EXISTING	Stationary non-emergency CI engines <30 l/cyl, <300 HP	NA	No requirements	No requirements	NESHAP Subpart ZZZZ
NEW	Stationary CI <30 l/cyl	Ordered after 7/1/05 Mfg after 4/1/06	15 ppm	Model year 2014 and newer: 15 ppm	NSPS IIII
MOBILE SOURCES					
ALL	Non-Road Locomotive, and Marine (NRLM)		15 ppm	15 ppm	
ALL	On-Road		15 ppm	15 ppm	

Alaska has many homes and lodges with generators. Generally, these engines fall into the under 300 HP category. When used in areas accessible by vehicle (i.e., on the road system) and if they were ordered after July 1, 2005 and manufactured after April 1, 2006, these engines currently require ultra low sulfur diesel (15 ppm) (ULSD). Older engines and those used in areas off the road system (in areas accessible only by plane or seasonal ferry service) can still use higher sulfur fuel.

[1] FAHS, Federal Aid Highway System – You can drive there from the Lower 48 or it has regular drive-on/drive-off ferry service.

[2] Rural – Vehicles may be present but roads do not extend to outside areas. Seasonal or passenger ferry service only.

[3] Abbreviations used: liters per cylinder (l/cyl), compression ignition (CI), hazardous air pollutant (HAP), horsepower (HP), parts per million (ppm).

Analyses of Available Literature

Before discussing the uses of specific additives in Alaska, several general observations can be made. The first is that engine manufactures require the use of a fuel that meets ASTM D975 specs, but strongly recommend against the use of any other additives in their engines, especially those that create metallic deposits on surfaces inside the engine. They also discuss the importance of water management in the fuel handling process, with specific recommendations with regard to fuel storage, filtering, fuel line configurations to manage this issue. They state that a well-maintained diesel engine operates at maximum efficiency already without the need for any third party additives.

The second general observation comes from the EPA's test program. Reviewing the EPA testing procedures, it is hard not to be impressed by the rigor of the process used: identical cars are tested on the same test track, driven by the same group of drivers; fuel caps are equipped with locks to prevent any tampering with the fuel; and much care is taken to assure that all test procedures eliminate as many sources of variability as possible. The EPA states, categorically, that to date, no additive or device has been produced by any vendor that can be shown to improve engine efficiency of a well-maintained modern engine. While this testing has been mostly done on gasoline automotive engines, it seems likely that these results also apply to diesel engines used in stationary power applications.

Experiences of Alaska Utilities

Data Collection Methods Used in this Study

The use of additives in the whole fuel supply chain supporting Alaska Diesel Electric Utilities was surveyed in this study. Data on user experiences were collected through telephone and e-mail interviews. Each interview asked individuals at organizations to share any experience they had using fuel additives, what types of fuel they worked with, and if they had any fuel problems that might require an additive. Notes were made of each conversation, and some organizations were contacted several times in order to clarify details. Organizations included utilities, fuel distributors, and refineries.

According to the 2011 Power Cost Equalization Report, 183 communities participate in the PCE program. Of these communities, 52 were part of the Alaska Village Electric Cooperative; 21 were served by the Alaska Power and Telephone Company; and the Inside Passage Electric Cooperative, Middle Kuskokwim Electric, TDX Power and the North Slope Borough each serve between 3 and 7 communities. Small samples of communities in each of these larger organizations were contacted, as well as an operations manager knowledgeable about the organization's additive practices. Finally, three large utilities that are not part of the Alaska Power Association (APA) or the PCE program were interviewed: Alaska Electric Light and Power in Juneau, Sitka Electric, and the University of Alaska Fairbanks (UAF) power plant. In total, this study attempted to contact 96 diesel power utilities and communities and received substantive responses from 82. Respondents burned 24 million of the 28 million gallons of diesel fuel consumed in 2011 by PCE communities; additional fuel was burned by the non-PCE communities that responded. The 96 utilities included every utility that participates in the PCE program or is a member of the APA and uses diesel generation. This group omits other utilities that do not qualify for the PCE subsidies, as well as utilities that qualify but did not file for the PCE subsidy. It also omits commercial generators, such as those used at mines or fish processing plants. Diesel engines used in fishing, trucking and construction industries were beyond the scope of this study. Figure 5 shows the geographic distribution of surveyed utilities and communities.

Ten diesel fuel distributors and refiners were identified during conversations with utilities and later interviewed: Delta Western, Crowley, Vitus Marine, Tesoro, Petro Star, Flint Hills, Everts Air Fuel, Ruby Marine, Fisher's Fuel, and Shoreside Petroleum. These companies were very consistent in their responses: because they sell different types of fuel, they could not give a simple description of their fuels' properties. However, they asserted that all of their fuel meets the appropriate ASTM International standards, and they use additives as needed to ensure their fuel's quality.

Additives are sold by a variety of vendors in Alaska. This project was originally motivated in part by a perception that numerous vendors were aggressively marketing their products to utilities throughout the state. While numerous utilities mentioned that they had been contacted by additive vendors, only one vendor was identified as actively promoting a product (EcoSave Fuel Catalyst) to multiple utilities. A handful of other additive vendors are involved with Alaska utilities, but their efforts were solicited by representatives of the utilities themselves rather than the other way around. For instance, Alaska Industrial Supply provides information about additive products to the Yakutat power company at the plant manager's request.

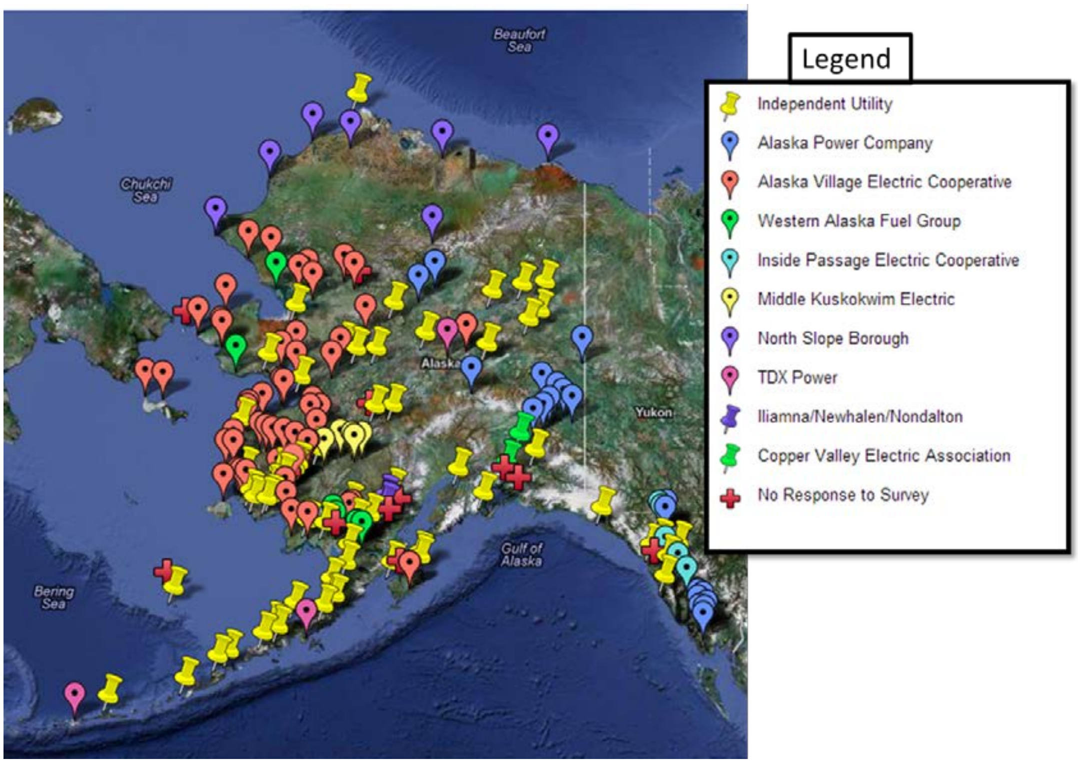

Figure 5. Utilities and organizations serving rural Alaska fuel needs.

Diesel Electric Generators used in Rural Alaska

Most electricity generated and consumed in the U.S. is provided by large centralized power plants—natural gas, coal, nuclear and hydropower plants—and distributed to consumers through a network of transmission and local distribution lines [82]. However, many communities in Alaska are too small and isolated to justify the capital expense required to build electrical interties and large electricity generating plants. For those communities, the diesel generator remains the primary source of electrical power. The diesel generators are small; outside of the railbelt, most diesel generators in Alaska utilities are rated to a capacity less than 500 kW (see Figure 6). While many advocate alternatives, including wind power, small scale hydro, tidal, geothermal, or biomass systems, in many places the diesel generator remains the most cost-effective, established and dependable option, despite the recent rise in fuel prices.

The past few decades have seen significant improvements in the performance of diesel engines. Improvements in fuel injection systems, especially the use of electronically controlled injection patterns, have largely eliminated the black smoke particulate clouds typical of diesel engines from a few decades ago. The use of turbo chargers to increase compression ratios has also led to improved efficiencies. The relatively recently mandated introduction of Ultra Low Sulfur Diesel (ULSD) and use of exhaust clean-up technologies has led to further reductions in particulates.

Despite these recent advances, rural, diesel-powered energy remains expensive in comparison to the energy resources available elsewhere, due to the cost of fuel. A well-run, larger engine installation among the relatively smaller utilities in Alaska can produce 14-16 kilowatt hours per gallon of fuel consumed. If fuel costs are $5 per gallon (many communities were approaching this cost during the fuel cost spikes of 2008 and 2009), the fuel-only cost is about $0.33 per kilowatt hour generated, roughly ten times more than the fuel cost for natural gas or coal fired electricity used by customers on the grid. This creates a very strong incentive for diesel generator plant operators to find ways to improve the efficiency of their engines.

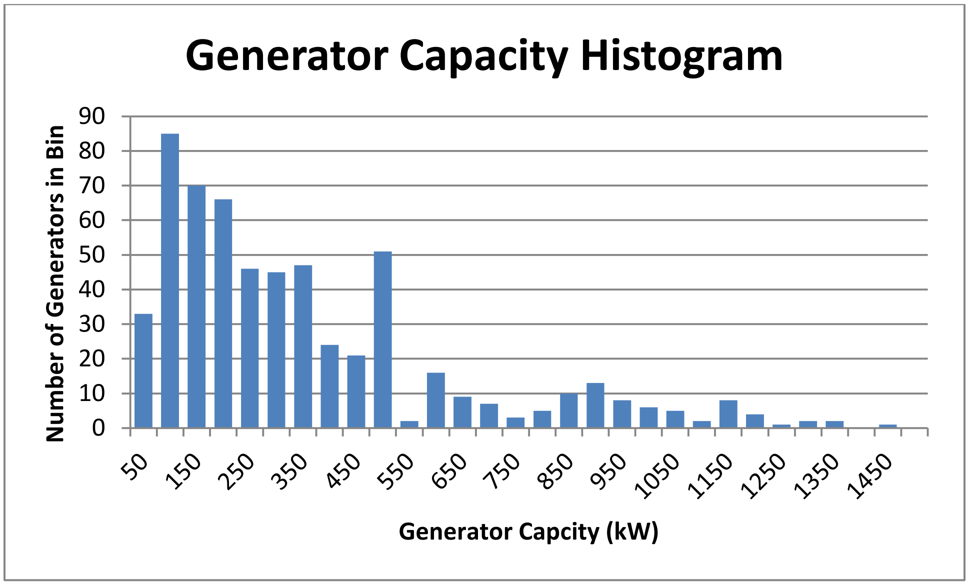

Figure 6. Histogram of installed generators in rural Alaska utilities. The data are from two AEA surveys of generators in rural Alaska. The data include 181 communities that presently operate 622 diesel generators.

Fuel Survey Results

Diesel Fuel Purchase and Delivery Systems in Alaska.

Alaska electric utilities purchase diesel fuel through a variety of processes depending on their size and cooperation with other utilities. In addition to the large utility organizations like AVEC and APC, the Western Alaska Fuels Group (WAFG) is a fuel purchasing consortium that coordinates the fuel purchasing of Kotzebue, Nome, Dillingham, and Naknek (Aleknagik and King Salmon are intertied to Dillingham and Naknek, respectively). The remaining utilities in the state are owned independently, and depend on commercial fuel suppliers for fuel.

When Alaska electric utilities purchase diesel fuel, contractual specifications based on ASTM D975 are generally given. However, some organizations and independent utilities give specific specifications for particular parameters, as permitted in ASTM D975. For instance, Juneau's Alaska Electric Light and Power includes pour point and cloud point specifications in their fuel purchasing orders that are more stringent than those in ASTM D975 [83]. Similarly, the WAFG defines pour point, Btu per gallon, and lubricity specifications that differ from those in ASTM D975.

Fuel suppliers routinely adjust fuel pour point and lubricity with additives, and the cost of these additives is included in the purchase price of the fuel. Pour point temperature can also be managed by refining a lighter grade of diesel fuel (closer to specs for number 1 fuel rather than number 2), but these lighter grades of fuel have lower energy content per volume, and can trigger a cost penalty for the Btu/gallon standard provided in WAFG's contract [51]. The WAFG puts its fuel order out to bid annually, and distributors compete to supply fuel that meets their specifications at the lowest possible price.

Many utilities do not set their own fuel specifications or have a formalized bidding process. AVEC, for instance, generally burns straight No. 1 diesel to avoid confusion between summer and winter fuels. However, villages occasionally use some No. 2 fuel if it is more available than No. 1. Many of the villages AVEC serves are extremely isolated, making it difficult to get fuel delivered at all, let alone with strict specifications or additive requirements [52]. This sentiment was shared by many independent utilities that rely on their fuel supplier to provide satisfactory fuel for their location and application, and have no formal specifications or procedure for testing the fuel that is delivered. However, the fuel suppliers purchase fuel that is certified by the refineries to meet ASTM D975 specifications for delivery to their customers. This study did not identify any issues with either miss-identified fuels, or fuels that did not meet ASTM D975 specs, other than fuels delivered to small communities that were identified as heating fuels, but used for power generation.

Sources of Fuel

It might be expected that given the large crude oil production in Alaska, diesel fuels used in Alaska would also come from this source. Indeed, Alaska crude oil constitutes a large portion of the base stock for diesel fuel in the state [85]. However, bulk fuel purchasers have indicated that fuel shipments also come from other sources, including the U.S. West Coast, Canada [86], and (in the case of the Russian ice breaker delivering fuel to Nome in the fall of 2011) from a terminal in South Korea, probably from oil fields in the Middle East. [87] .

Delivery of Fuel in Rural Alaska

Diesel fuel is delivered to utilities in a variety of ways. In communities located in ice-free coastal areas or on the road system, fuel can be delivered year round, and it is not necessary or prudent to store large volumes of fuel at the utility. Unalaska is one such community, where the utility purchases fuel from a delivery company several times a week, and does not maintain any bulk storage [88]. In these communities, diesel fuel can be purchased with properties adjusted for seasonal temperatures, with heavier No. 2 fuel used in the summer months, and lighter No. 1 burned in the winter.

However, many Alaska communities are off-road and icebound for much of the year, requiring that sufficient fuel be brought to the community during the ice-free summer months by barge, requiring bulk storage. In these communities, a single grade of fuel is usually delivered to eliminate the possibility of confusion, so all the fuel must be able to flow at the minimum annual expected temperature. In coastal communities, this can be done by adding pour point depressants to No. 2 fuel (good to about -35°F), but inland communities often experience much colder temperatures (-50°F or colder), and thus need lighter No. 1 fuels. Many utilities in these communities own and manage their own bulk fuel storage tanks.

Communities located off the road system and distant from navigable rivers are the most difficult to supply with fuel. These communities must resort to air delivery. Air delivery is expensive: while the exact cost depends on the size of delivery, length of runway, and the delivery distance, case studies by the Institute of Social and Economic research suggest that the typical air delivery cost is close to $2.00 per gallon [85]. Everts Air Cargo and Brooks Fuel, Inc. provide most of the airborne fuel deliveries in the state and service roughly 25 mostly small communities. Cargo planes with a capacity of 5,000 gallons transport the fuel.

Most of the air-delivered fuel is No. 1 heating oil, but Everts occasionally delivers No. 2 fuel and unleaded gasoline as well, which indicates that at least some of these communities are using heating fuel for power generation. Heating oil is similar to diesel fuel, although some of the specifications are less strict. There is no ultralow sulfur requirement, for instance, nor is there a cetane number requirement for heating oil. The price difference between ULSD and heating oil varies depending on the relative supply of each type of fuel. However, for villages purchasing fuel from Everts air, ULSD is typically 20–50 cents more per gallon than heating oil [89]. Since the EPA does not require rural Alaska utilities to use ULSD yet, it makes sense for them to purchase heating oil from Everts for their older diesel gensets. It is not clear what would happen if heating oil were used in a tier 4 engine, although it is expected that the exhaust aftertreatment system would likely fail due to plugging with particulates.

Emergency fuel deliveries can also drive fuel prices up. The most famous recent example occurred in late 2011 and early 2012, when a coast guard ice breaker and a Russian tanker were forced to team up to bring fuel to Nome in January. Unusually forbidding weather or poor planning can cause fuel shortages that require creative and expensive fuel deliveries.

Aftermarket Additives Survey Results

The utility interviews revealed that aftermarket additive use is not prevalent, but still fairly common in Alaska. Out of the 82 utilities that responded to our questions, 21 (25%) reported having some experience with aftermarket additives or explicitly requesting before-market additives. Utilities purchase the additives to address a variety of concerns about their fuel (see Figure 7).

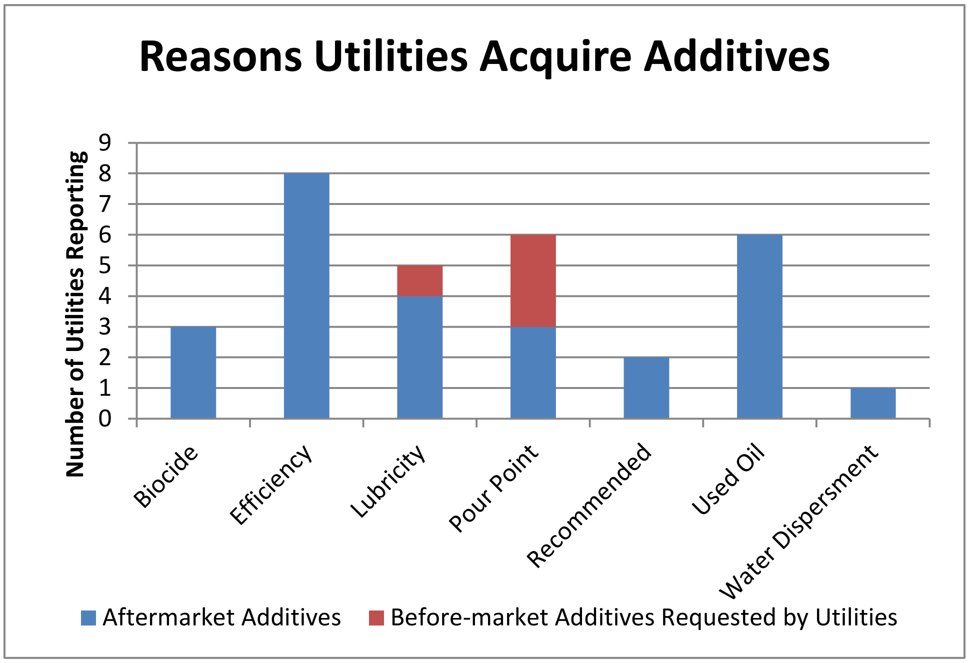

Figure 7. Reasons utilities acquire additives.

There are many reasons that utilities may choose to purchase, test and/or use aftermarket additives. Many utilities in Alaska make relatively small fuel purchases and cannot afford to request fuel made specifically for their needs. Others experience unusually cold weather, biological growth in their fuel tanks, or some other unforeseen circumstance that requires an aftermarket additive. These additives are often added into tanks where the utilities store their fuel. A picture of the "splash" technique for adding an additive into a Yakutat Power tank (see front cover) illustrates how this is done at one location, and we believe this technique to be representative of the way it is done in other remote communities.

Since some utilities purchased additives for different, multiple reasons, the additive's use is included multiple times in the Figure 7 data. Two utilities used additives simply because they were recommended by trusted sources: a Caterpillar representative in one case, and Craig Taylor Equipment in the other. These two utilities are in the category titled "Recommended."

No utilities reported purchasing an additive in order to clean their fuel injectors, but six of the additives that utilities purchased for other purposes also claim to remove deposits from injectors. It is interesting to note that while utilities have specific motivations for using additives, the products that are available on the market often treat fuel properties much more broadly.

It is difficult for utilities to measure the efficacy of some of the additives they use, even when these additives change a measurable property. Lubricity additives, for instance, are necessary in fuel with low lubricity in order to prevent unnecessary wear in the engine. The standard lubricity measurement procedure is the high frequency reciprocating rig (HFRR) test described in ASTM D6079 [21]. Fuel suppliers in Alaska generally guarantee that their fuel meets the ASTM lubricity standard based on this test. Utilities do not have the resources to conduct this test on site, but they could ship a fuel sample to a laboratory to have their fuel's lubricity tested. Southwest Research Institute, for example, will conduct HFRR tests for $275 per assessment [90]. No utilities reported submitting a fuel sample for testing by such an independent laboratory, so the only way they determine the efficacy of an aftermarket lubricity additive is to try to determine if its use has decreased maintenance requirements for their diesel engines.

Pour Point Depressant Use

Pour point additives are often blended with fuel as a preventative measure. If an additive-fuel mix does not gel at moderately low temperatures, it is difficult to determine if the fuel would have gelled without the additive without laboratory test data. However, Alaska utilities have had a handful of instructional experiences. The Western Alaska Fuels Group's specifications have required fuel with a pour point depressant for many years. They have never had trouble with the cold flow properties of their fuel, even though winter temperatures would typically gel fuel that meets the group's energy content specifications [51].

The WAFG takes advantage of its practice of purchasing fuel in bulk to require that the pour point additive be blended in before delivery, with satisfactory results. Two utilities from the WAFG are included in Figure 8 (Nushagak Electric and Nome Joint Utilities did not respond to the survey). The Iliamna/Newhalen/Nondalton utility also reported using a before-market pour point depressant that was blended with the fuel while the line haul barge was being loaded. The additive did not function properly and the fuel gelled at -15°F. Three other utilities in Alaska have blended aftermarket pour point depressants into their fuel after it was delivered with mixed success. Of the three utilities, only False Pass reported having success with an aftermarket pour point depressant. False Pass used the additive when they had an unusually long cold snap with temperatures near 0°F (still mild in comparison to the temperatures many utilities face, and close to the natural pour point of many No. 2 diesel fuels), and they had no trouble with fuel gelling while using the additive. One of the other utilities reported that they only tried a pour point depressant once many years ago, and it allowed water to pass through their filtration system [91-93]. On the other hand, the utility serving Iliamna, Newhalen, and Nondalton reported using pour point suppressed fuel, but the fuel still gelled at -15°F [92]. This indicates the uncertainty inherent in using aftermarket additives that are not specifically designed to match the fuel and blended at a designated mixing facility. The fuel consultant for the WAFG also emphasized this point, reporting that if a pour point depressant can be added when the fuel is hot, it mixes well, and a lower cost additive can be used. In cases where a pour point additive is blended with cold fuel (such as at the site of a small utility), it requires a more expensive additive, and it is difficult to get the additive properly mixed into the fuel [51].

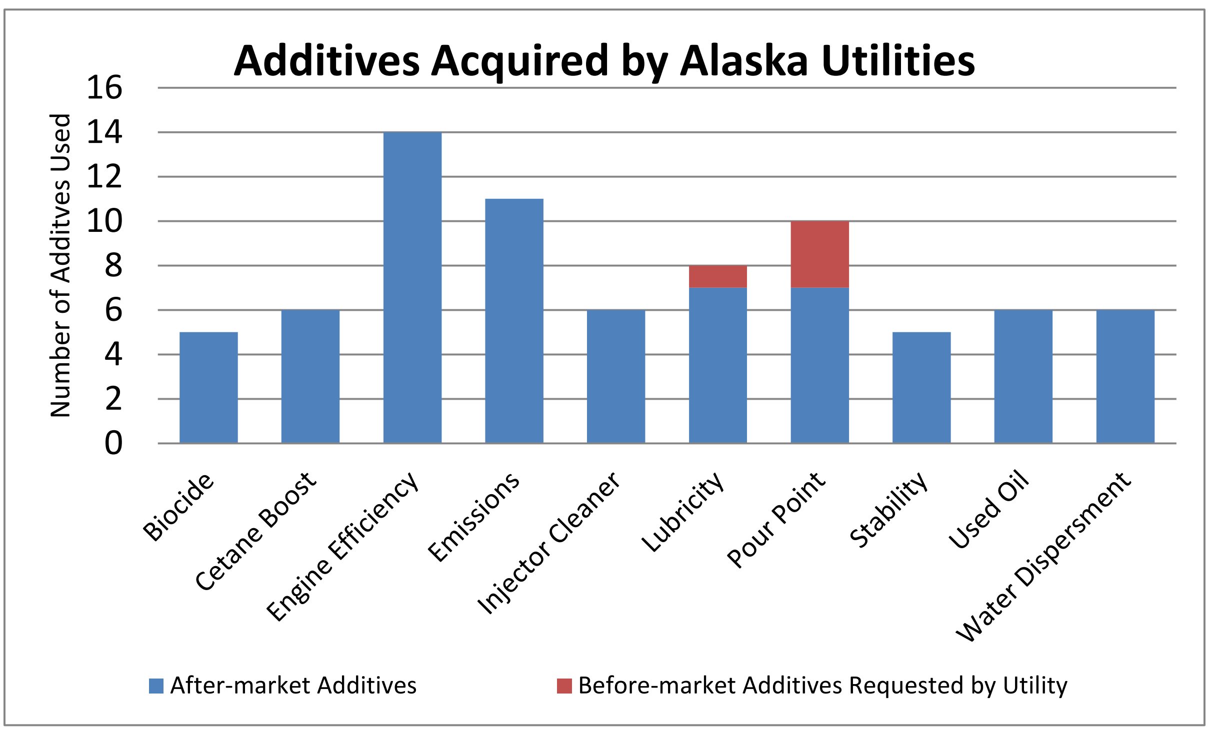

Figure 8. Properties of additives acquired by Alaska utilities. All the additives mentioned by utilities during interviews are included, even if one utility used multiple additives. Products that address multiple fuel properties are counted in each category to which they apply. This means that one utility can have many entries associated with it.

Lubricity Additives

All ULSD fuels require the use of a lubricity additive to meet the ASTM D975 standard requirement in the scuff ball test. Any fuel that does not meet this specification is not appropriate for use in a diesel engine. In many cases, this lubricity additive is metered into the fuel when being transferred from the dock to the on-shore storage facility. The Western Alaska Fuel Group requires a higher level of lubricity than required by ASTM D975, which is accomplished by increasing the amount of lubricity additive mixed in the fuel.

Three utilities in Southwest Alaska, as well as the North Slope Borough, began using aftermarket lubricity additives after switching to ULSD [94-97]. Two of these utilities began using the additive because they heard that the ULSD would have a lower lubricity than Low Sulfur Diesel. Egegik began using the additive because Crowley offered to blend it with their fuel at the delivery dock (it is not clear if Egegik was billed for the additive product). The utility in Pilot Point reported that they had three fuel injectors fail in 18 months after switching to ULSD, and they began blending engine oil into their fuel to improve the lubricity in August of 2012. However, there is some concern that the engine oil is settling out of the fuel and it is unclear whether this treatment has been effective. None of the utilities using an aftermarket lubricity additive have measured the lubricity of their fuel or observed a decrease in engine maintenance attributable to the lubricity additive so far.

Biocides

Biocides are typically used after a microbial growth begins to clog filters or cause other engine problems. IPEC and Manley were the only utilities in Alaska that reported experience with biological growth in their fuel tanks. Manley reported successfully removing the growth by using a biocide additive and physically cleaning the tank [98]. IPEC reported some success with cleaning the tanks and using a biocide, but later installed new tanks that completely eliminated the problem [93]. The utility in Unalaska blends a biocide into its fuel tanks annually to prevent biological growth. Unalaska has never had trouble with biological growth, but it is uncertain if the additive has prevented biological growth or if the fuel would have remained clean even without the additive.

Robert Dryden noted that "all communities south of Naknek use biocides in their fuel" [51], but many of the utilities in these coastal communities do not maintain their own bulk storage facilities, and instead purchase fuel in smaller volumes from local fuel distributors, so they are likely purchasing fuel treated with biocides by the vendor.

Long-term Fuel Storage Issues—Especially Water in Fuel

Long-term storage of diesel fuel is problematic for several reasons. As fuel tanks heat and cool during daily temperature cycles, the air (and fuel vapor) above the fuel expands and vents during the warmer part of the day, and contracts and pulls fresh air into the tank during the cooler time. Along with the fresh air sucked into the tank is some water vapor, which then condenses on the side and flows to the bottom of the tank. While the water introduced in a single cycle is minimal, over the course of a year (or years, if the water is not drained), the water accumulation can be significant. Water is also often introduced during ocean-going barge transport—"water comes in off the barge" [51].

In addition to promoting biological growth, water can damage injectors. Some engines are extremely intolerant of any water, as a droplet of water in the fuel can cause a steam explosion at the injector tip, destroying the nozzles that control the fuel spray pattern into the cylinder, resulting in immediate engine failure and expensive repairs. Other engine designs are more tolerant of water in the fuel, but water still results in a loss of lubricity in the injection pistons, causing much more rapid wear of the injectors. For this reason, water management in every aspect of fuel handling is crucial, and an important part of diesel engine manufacturers' recommendations [50].

Additive Blending Procedures

Before-market additives are often necessary to bring fuel into conformity with ASTM D975 standards. In some cases, when fuel is purchased by a consortium, before-market additives are used to meet the consortium's standards as well as the ASTM standards. Whenever possible, it is advantageous for utilities to request that their supplier provide fuel with the desired additives already blended in rather than blend the additive with the fuel themselves. This way, utilities can take advantage of the blending facilities and fuel expertise available at refineries.

Figure 9 through Figure 11 illustrate the advanced blending process used at the PetroStar refinery in North Pole, Alaska, to raise the lubricity of their diesel fuel. The first images show the blending facility and pump station, and subsequent images go inside to show the blending meter and blending apparatus. Figure 12 shows the High Frequency Reciprocating Rig that is used to test the fuel, ensuring that the additive has had the desired effect on lubricity. Some *ad hoc* testing or site-specific uses of additives requires introducing the additives to the onsite fuel storage, the so-called “splash” technique shown in Figure 13.

Figure 9. Diesel fuel delivery station at PetroStar Refinery, North Pole, Alaska. The gray building just to the right of center houses the metering and injection of additives. Truckers enter orders for fuel and fuel blends in the brown building at the front right of the gray building. They use an advanced control and metering system for dispensing the requested fuel into delivery trucks positioned in the station. Fuel storage tanks can be seen in the background. Photo by Frank Williams.

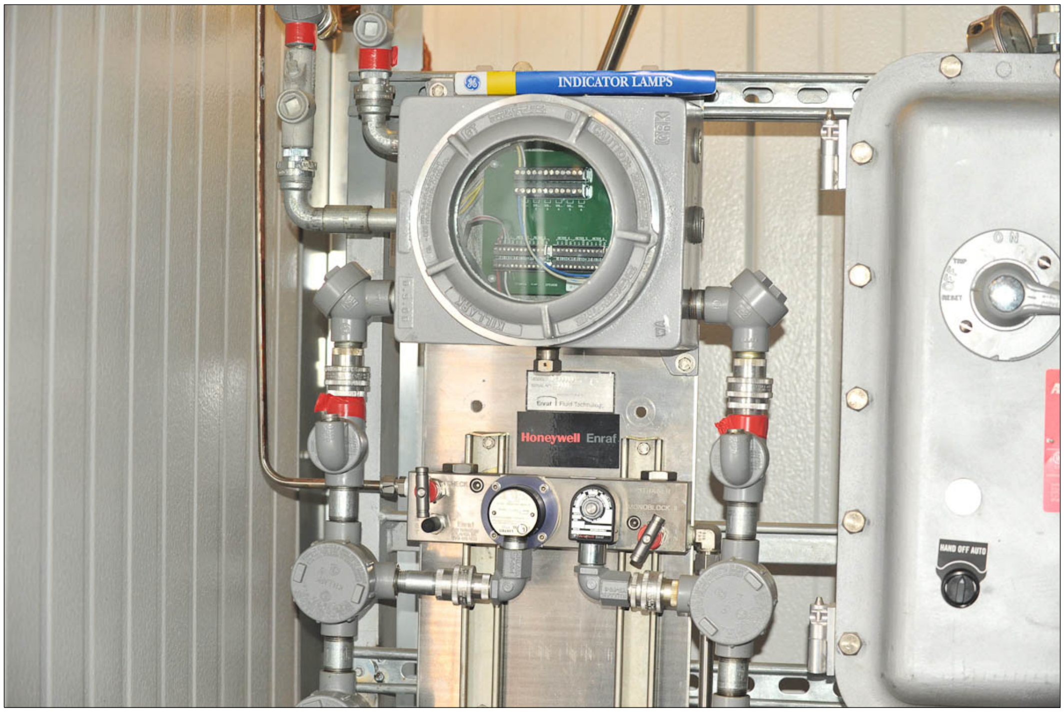

Figure 10. Blending meter for lubricity additive, PetroStar Refinery, North Pole, Alaska. Lubricity additive is precisely and accurately metered and pumped with electronic control for injection into the diesel fuel that is pumped into delivery trucks outside. Photo by Frank Williams.

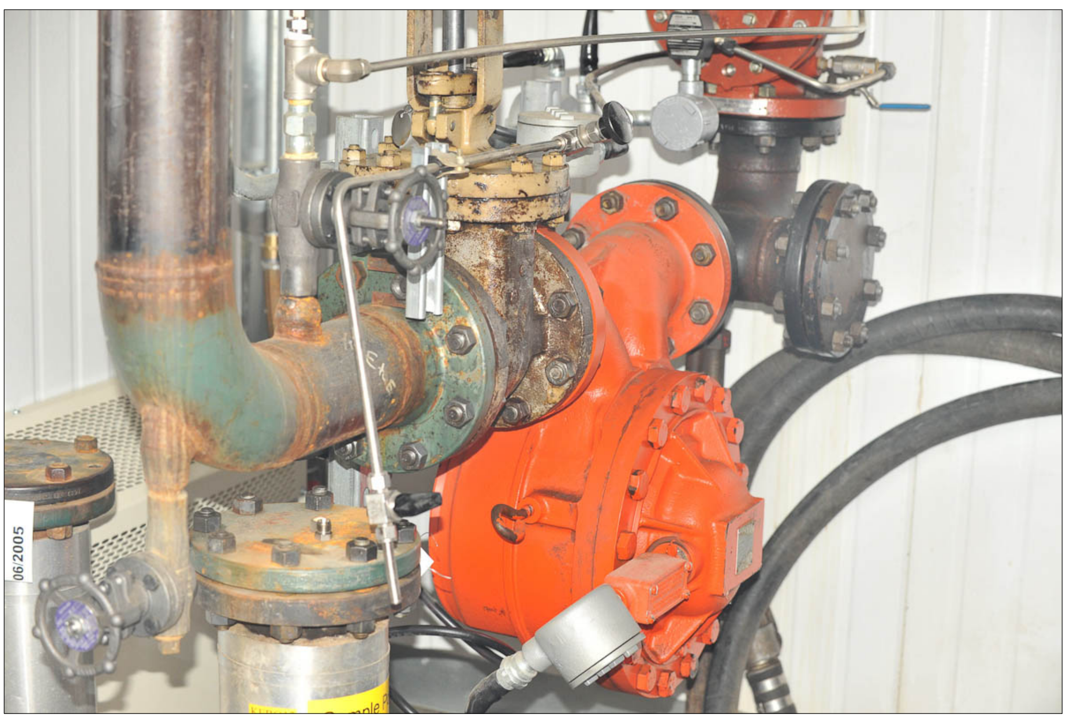

Figure 11. Mixing point for lubricity additive. Lubricity additive enters the fuel stream from the electronic metering system through the smaller gray isolation valve left of center above the large green elbow. The additive mixes with fuel flowing in the larger pipe with a green elbow. The fuel and the additive mixing is assured as the components flow through the meter (orange) and on to the awaiting truck. Photo by Frank Williams.

Figure 12. Scuff ball test rig, PetroStar laboratory. Enables PetroStar to measure the lubricity of its fuel and ensure that it meets ASTM D975 specifications. Photo by Frank Williams.

Figure 13. "Splash blending" of an additive at the Yakutat Power for testing purposes. Note fuel truck delivering fuel to the power plant and the worker adding a liquid to the tank during fuel delivery, using the mixing provided by the fuel movement during transfer to mix the additive with the fuel. Photo by Scott Newlun.

Testing of Aftermarket Additives by Alaska Utilities

When utilities do purchase additives, it is most often because of a recommendation from an unaffiliated third party rather than information directly provided by an additive vendor. However, AP&T and AVEC, the two largest rural Alaska utility organizations, both report that many additives are pitched to them, and AP&T has tested some products. A few other utilities also reported that an additive vendor had contacted them in the past, but the utilities expressed no interest in their products and generally reported remembering neither the name of the vendor nor the product they were selling.

As noted in the literature review, claims of significant efficiency improvements to well-maintained modern engines through the use of fuel additives are directly challenged by many sources, including the EPA, the FTC, all the major diesel engine manufacturers, and fuel suppliers. In addition, many of the additives and devices may have significant downsides to them: some additives create deposits inside the engine that may be abrasive and result in shorter engine life, and some devices, such as those providing hydrogen to the engine, actually are making an explosive mixture of hydrogen and oxygen, and are a significant safety hazard.

Several issues complicate the evaluation of all these claims. The first is the natural variability of short-term fuel consumption measurements. Variables such as ambient temperature and relative humidity have been shown to have an effect of at least a few percent on engine efficiency, so a short-term experiment might show an efficiency improvement due to some other factor. This is compounded by the natural tendency of people to disseminate positive results, but suppress null or negative results, especially if one is trying to sell a product. In addition, the products are often being pushed by "true believers," who are convinced that they have a product that will benefit their customers. Often these individuals have invested their own funds to obtain the rights to distribute the products, and are reluctant to consider information that does not support evidence that indicates that their product may not be as useful as they believe.

Age of Diesel Engines used for Testing Additives

In reviewing the claims made by additive suppliers, it was apparent that some additives were more likely to have some beneficial effects in older engines than in current models. For example, one additive apparently contained some form of ferrocene, a substance sometimes used as a lead substitute for older gasoline engines designed for use with leaded fuels. Older diesel engines tend to be both dirtier (implying that at least some of the fuel value leaves the engine as soot) and less efficient (so there is greater room for possible improvement from an additive). Based on these observations, this study included a general survey of the current fleet of engines used by current diesel power utilities.

The age and size of diesel engines is based on information provided from utilities that chose to participate in the Alaska Energy Authority Village Power System Assessment and Inventory, detailing the installed diesel generators in Alaska as well as the operational metrics for the utility. The information documents the size, model, make and condition of engines in powerhouses throughout the state. The serial number of the engines was also provided, which we used to look up the build dates of over 500 engines throughout the state from the three most prominent engine manufacturers in the state.

From the figures below (Figure 14 and Figure 15), we see a significant shift to John Deere engines from Caterpillar. Not evident from these charts is the additional observation that Caterpillar tends to dominate the larger engine market in Alaska (sizes greater than 500 kW), while John Deere dominates the smaller engine market. The majority of engines purchased since about 1995 are equipped with electronic fuel injection systems.

Efficiency Enhancing Additives

Seven utilities reported that they have tested additives or devices intended to improve the efficiency of their diesel engines. Many of these tests were conducted using additives or devices provided at no charge by the suppliers, and thus do not represent a cost incurred by the utility or their customers.

These tests are distributed among all regions of Alaska except the North Slope. Out of the seven utilities that have tested efficiency enhancing products, Unalaska and Yakutat reported having some success. Unalaska installed a combustion catalyst device in the fuel supply line of many of their engines in 2008 and reported an efficiency improvement of about 3% on their older engines [88]. Since then, however, Unalaska has gotten new engines and has not been able to purchase a version of the device that will fit them. Yakutat has tried several additives and retrofit devices in order to try to improve engine efficiency. Most recently, Yakutat tested an additive by Centron. The product purports to serve many functions, including reducing surface tension to allow for a more complete burn of the fuel, and acting as a detergent to clean deposits in the fuel injectors. This resulted in a 6-7% improvement in efficiency in preliminary tests, although the results are not conclusive [100]. Worth noting is that this additive was provided at no cost to the utility, and so it is unclear what the cost of the additive to the utility would be.

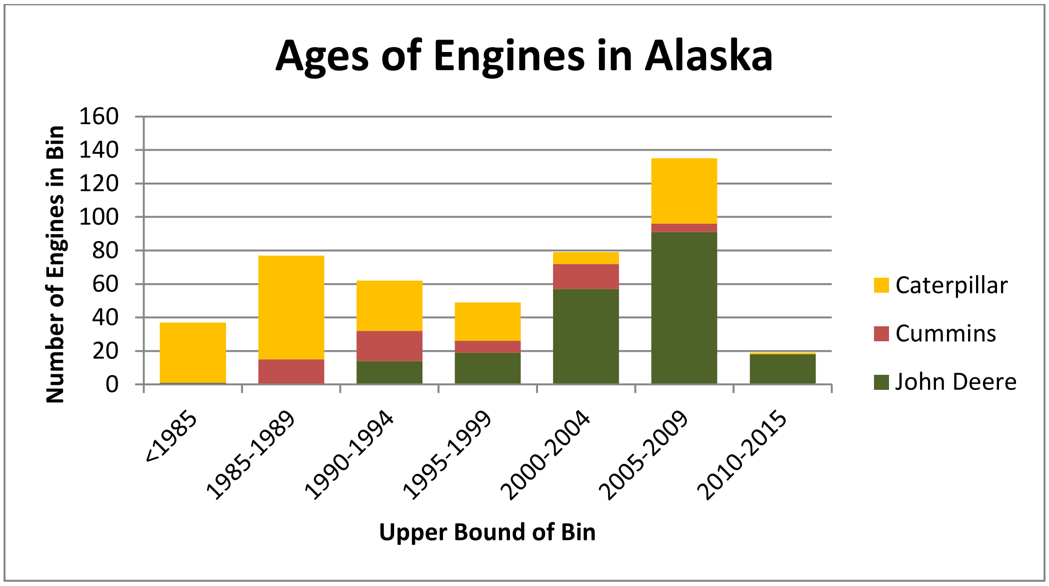

Figure 14. Engine ages for Cummins, Caterpillar, and John Deere engines reported to the Alaska Energy Authority. For the 99 other engines included in the AEA survey (including 58 Detroit Diesels), build dates were not recorded.

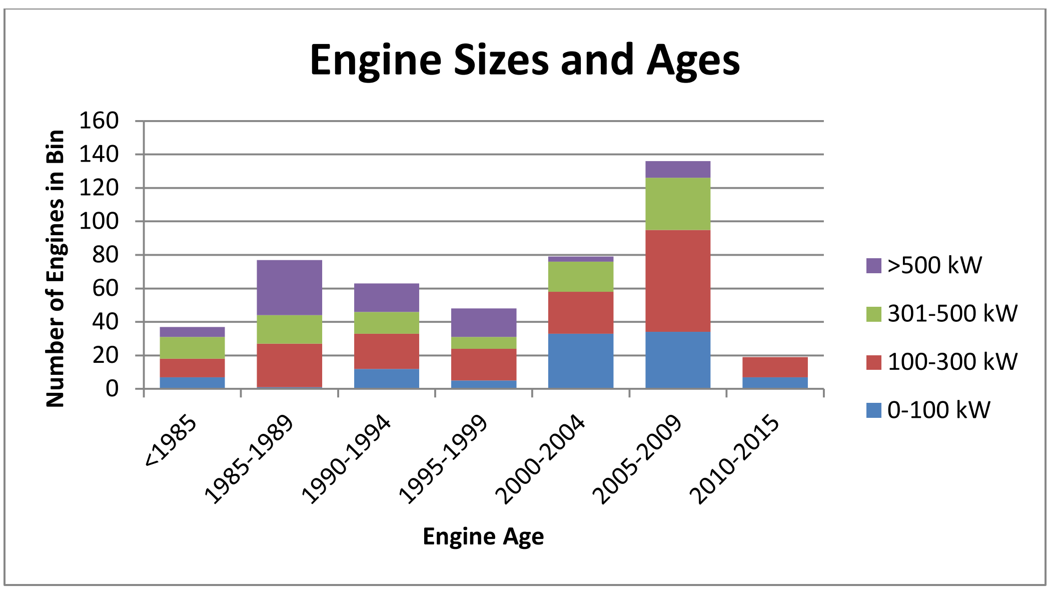

Figure 15. Age and size of engines in Alaska utility fleet.

Two utilities are in the process of testing an additive called EcoSave. Neither utility was prepared to state whether they could see efficiency improvements with the additive or not, although one reported that their exhaust temperature was reduced significantly and preliminary results suggested some improvement. The test at that site is still ongoing. The other site reported problems with an additive dispenser device that has delayed their test. The device is designed to meter the injection of additives into the fuel stream to precisely match the desired concentration, but it broke early in the testing process [101, 102]. Some concern has been raised over this particular additive, however, as it appears to contain a compound that coats the inside of the engine with a metallic layer, which, as noted above, is specifically forbidden by engine suppliers. Additional concerns about this product include a patent suit against the manufacturer of the product, and an SEC investigation into one of the marketing companies providing this product.

Efficiency Enhancing Devices

Two utilities reported testing magnetic fuel treatment devices, and neither observed a significant improvement in engine efficiency [51, 74]. Two other utilities tested devices that added small amounts of hydrogen to their engines [88, 103]. The hydrogen did offset some fuel use, but there were no net savings because the utilities used electricity from their engines to produce the hydrogen.

Finally, AP&T has tested several products that marketers claimed would improve efficiency and offered free trials. None of the products AP&T tested were found to improve efficiency [104].

Used Oil

Although not necessarily a fuel additive, six utilities reported filtering and then burning used oil in their engines. The practice is becoming more popular as AEA continues to install used oil blending systems in new power plant modules. If it can be done without producing toxic emissions or damaging engines, burning used oil provides a convenient solution to the hugely difficult problem of disposing of used oil in remote locations.

Some utility engineers and operators expressed concern that burning used oil would increase wear on their engine. Indeed, Caterpillar states that blending used crankcase oil with diesel fuel can result in fuel filter plugging and fuel system deposits; some company materials also warn that burning used crankcase oil can cause engine emissions that are out of compliance [25]. Detroit Diesel also forbids burning used lubricating oil in its engines. However, neither the Alaska Energy Authority nor any of the utilities that burn used oil reported any increased maintenance attributable to the used oil.

Other statements from major engine manufacturers also condone burning used lubricating oil in diesel engines. Cummins, for instance, allows burning used lubricating oil if the engines are neither required to use ULSD nor have an exhaust gas aftertreatment system. Caterpillar also condoned burning used oil in an earlier document [105], although the 2010 Machine Fluid Recommendation (referenced above) supersedes the older publication.

Given the positive experience of utilities in Alaska and the unique challenge of disposing of oil in rural Alaska, it is reasonable for utilities to continue blending used oil with their diesel fuel. However, operators should be vigilant for increased fuel filter plugging or engine deposit formation due to the practice.

Which Utilities Use Additives?

We looked for correlations between the types of additives used and different utility characteristics. There is no obvious correlation between the size of utilities in Alaska and their proclivity to use additives, although the small sample size makes it difficult to prove or disprove a correlation (Figure 16). Note that about the same percentage of utilities from all population ranges have tested aftermarket products.

Discussion of Additive Use by Alaska Diesel Engine Utilities

Based on the literature review and the survey of Alaska power plants, several general observations can be made:

- Utility operators are largely familiar with appropriate ways to use legitimate additives (pour point suppression, lubricity and conductivity additives for ULSD, biocides where needed, and occasional use of injector cleaners.)
- Use of aftermarket additives is not prevalent, consistent with diesel engine manufacturers' recommendations that additives are not needed so long as fuel meets ASTM D975 specifications, and engines are well maintained.
- Utility operators understand the role of good O&M practices, including water management in stored fuel and the need to replace injectors when necessary.

- Most utility managers are suspicious of claims of significant improvements in efficiency above that of a well-maintained modern engine, and investment in these additives or devices remains low.

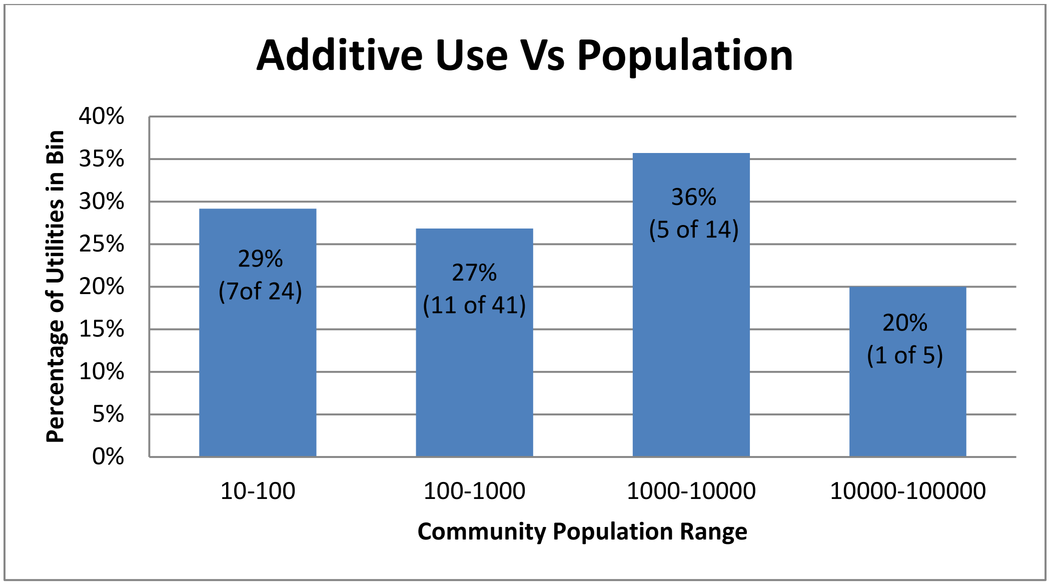

Figure 16. Additive use versus community population.

Several items of concern have also been noted:

- One utility reported use of a water dispersant, which is not recommended by diesel engine manufacturers, so some education in this matter appears appropriate.
- Several utilities are unclear about the appropriate use of lubricity additives in ULSD fuels, so some education in this matter appears appropriate.
- A few utilities appear to be using additives that might or might not be appropriate for their power plants, but the total investment in this does not appear to be excessive.
- The most common reason given for additive use is to improve efficiency, even though the EPA, the FTC, and all engine manufacturers indicate that there are no known products that can increase diesel engine performance above that of a well-maintained modern engine.

Experience of Fuel Suppliers in Alaska

Fuel suppliers offer a different perspective on fuel additives than utilities. While utilities are exposed to a sea of products available in small quantities from a plethora of companies, fuel suppliers typically purchase additives in bulk from a small number of very large companies, specifically Innospec, Infineum, BASF, Lubrizol, and Nalco. Interviews with ten fuel suppliers in Alaska revealed that lubricity and conductivity improvers are included in nearly all ULSD in order to meet ASTM standards. Pour point depressants are also often used by fuel suppliers in some regions, although they are less common in Alaska than in other parts of the U.S. due to the extremely cold temperatures in Alaska. These are the only types of additives that are typically included in diesel fuel delivered to bulk customers. Unlike gasoline, there are no standards for detergent additives in diesel fuel.

Pour point, lubricity, and conductivity additives are mixed at various stages in the supply chain. Some pour point additives, for instance, need to be blended with the fuel at high temperatures, and are added to the fuel at refineries as a result, while other pour point depressants can be added at lower temperatures [51]. This requirement seems to reflect the general wisdom of vendors and users of additives – good physical mixing of the additives into the fuel is imperative, and can depend upon the chemistry of the additive and the fuel stock as well as the temperature during the mixing process.

Lubricity additives are necessary in most ULSD fuels, but there are strict limitations on the maximum concentration of lubricity additives in jet fuel, because it can decrease the efficacy of fuel filters and water separators [106] due to the hydroscopic properties of the additive. The responsibility of meeting the ASTM lubricity standard often falls to distributors, who blend an additive with the fuel after it has been transported but before selling it to the consumer [15]. This is consistent with reports from Egegik that Crowley blends a lubricity additive with their fuel at the fuel dock. Without the lubricity additive, ULSD fuels most likely will not meet lubricity requirements—"If the lubricity additive is offered—take it" [51].

All fuel distributors in Alaska guarantee that their fuel meets ASTM specs. Distributors and customers do not generally test their fuel, but rather rely on the specifications their supplier reports. Refineries have testing protocols to assure that their product is up to spec. Tesoro, for example, reported that they test their fuel to make sure that it meets ASTM D975 standards monthly [15]. Utilities that are concerned about the lubricity or other properties of their fuel should contact their suppliers to see what types of additives are included in their fuel, and make sure that their fuel meets ASTM D975.

Conclusions

Fuel efficiencies achieved in large diesel engines are at, or are very close to, the maximum achievable. Fuel efficiencies associated with electrical power production from smaller engines generally cannot match those of larger engines because of physical design considerations combined with the same theoretical maximum combustion-cycle efficiency constraints. Therefore, additives cannot improve fuel efficiency more than a few percent if at all, and none have been documented to achieve that in well-maintained engines.

Treatment of diesel fuels to bring the fuel up to ASTM standards for lubricity is efficacious in reducing engine component wear, and for the most part accomplished for fuels used in Alaska. The best situations occur when the additive is introduced and well mixed by the fuel producer and/or bulk distributor.

While not replacing the need for regular maintenance, additives may clean engine components that show degraded performance because of the build-up of deposits. This may well be more valuable for older technology engines, as well as engines long into their prescribed maintenance cycle, as a means for restoring original performance.

Recommendations

Continue to assess the need for cleaning agents in fuels, and the appropriate use of those kinds of additives in engines of all ages to help ensure long life and manufactures' new-engine performance.

Work to ensure good mixing of additives into the fuels, with increased attention the closer the point of introduction of the additive is to the utility. Adding additives to fuel tanks adjacent to the power plant requires attention to the physical mixing, temperatures of the fuel and the additive, and the mixing ratio. These conditions are often better controlled during delivery of the fuel to the region, and best controlled by the fuel producer or bulk distributor.

Seek *bona fide* testing of additives where controlled conditions can be insured and thereby increase the credibility of the findings. At this time, no candidate additive for improving fuel efficiency has been identified for such extensive laboratory testing. Augmenting testing of additives or add-on devices at utility sites by use of unbiased, third-party analysts could bring more understanding of the testing and help identify promising additives.

Glossary

Additive	Any substance added to diesel fuel intended to change the properties of said fuel.
Aftermarket	After the final sale to the consumer.
ASTM D975	Standard Specifications for Diesel Fuel Oils, a group of specifications that define the limits of acceptable properties for use of fuel in a diesel engine. All diesel fuel sold in Alaska is based on this specification.
Before-market	In the supply chain, before the final consumer.
Biocide	Additive intended to kill any bacteria, yeast, or fungus that might grow in diesel fuel, especially during long-term storage, especially problematic in damp climates where water layers exist at the bottom of fuel tanks.
Cetane booster	Additive to allow for easier ignition of diesel fuels, important mostly for cold starts in winter, generally not used in utility applications.
Cloud point depressant	Diesel fuel additive intended to reduce the temperature at which the fuel becomes cloudy due to the formation of wax crystals in the fuel.
Conductivity	The ability of a diesel fuel to conduct electricity and prevent static discharge.
Diesel engine	A compression ignition engine operating on diesel fuel.
Diesel fuel	Any fuel intended for the sustained operation of a diesel engine, including petro diesel, bio-diesel, and synthetic diesel fuels. Most commonly petro diesel, comprised of all compounds distilled from crude oil between 200C and 350C. May also contain additives to bring fuel into compliance with ASTM D975.
Efficiency	From thermodynamics, a measure of the amount of chemical energy in the fuel converted to useful work. In diesel electric generators, measured either as a percentage (40%) or as kilowatt-hours per gallon of fuel (15.6 kW-hr per gallon).
Engine manufacturer	Manufacturers of diesel engines used in electric power generation, in this report, specifically Caterpillar, Cummins, John Deere, and Detroit Diesel.
EPA	The U.S. Environmental Protection Agency, responsible for the regulation of emissions from diesel engines and power plants.
Flash point	The temperature at which the vapors above a fuel can be ignited.
FTC	The U.S. Federal Trade Commission, responsible for review of claims of dramatically improved efficiencies by additive suppliers.
Fuel supplier	The entity an Alaska utility would contract with to supply diesel fuel, including refineries, barge companies, air transporters, or local fuel companies.

Heating fuel	Fuel intended to be burned for heat, often containing higher sulfur content. Can be used in older diesel engines, but is not compatible with EPA engine emission regulations.
Injector cleaner	A diesel fuel additive intended to remove deposits from inside engine, especially at fuel injector tips.
Jet fuel	Fuel intended for aviation use.
Lubricity	The ability of a fuel to lubricate the surfaces with which it comes in contact.
Modern diesel engine	Diesel engines of recent manufacture, including features such as electronic injection controls and turbochargers.
PM	Particulate matter emitted by diesel engines as a by-product of combustion, known as a health hazard, regulated by EPA. Much of the effort by the EPA over the last few decades has been aimed at reducing PM 2.5.
Pour point depressant	Diesel fuel additive intended to prevent the gelling of the fuel in cold.
Refiner	The entity that converts crude oil into finished fuel products, including diesel fuel, jet fuel, and heating oil.
Regulated emissions	EPA regulates the following emissions from diesel engines: CO (carbon monoxide), HC (unburned hydrocarbons), NO_X (nitrous oxides), and PM (particulate matter). Emissions regulations affect both diesel engine design and fuel standards.
Stabilizer	Diesel fuel additive intended to permit long-term storage of the fuel, usually an anti-oxidant used to prevent formation of solids in fuel. Not typically used in Alaska due to natural reduction in oxidation rates due to cold temperatures.
Third-party supplier	Vendor other than refiner, fuel supplier, or engine manufacturer.
ULSD	Ultra-low Sulfur Diesel, fuels refined to below 15 ppm sulfur, necessary for operation of EPA Tier 4 engines with exhaust aftertreatment systems. ULSD fuels require lubricity and conductivity additives to bring fuels into ASTM D975 specifications, usually added by fuel supplier.
Water dispersant	Additive used to cause water in fuel to mix with fuel and pass through engine, such as deicers typically used in gasoline engines. Generally not recommended for diesel engines.
Well-maintained diesel engine	Diesel engine performing at or near factory new performance specifications, maintained to assure proper combustion of fuel and high efficiency.

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