

Chapter IV: Fuel Standard Feasibility

A. Feasibility of Removing Sulfur from Highway Diesel Fuel

1. Sources of Diesel Fuel Sulfur

The primary sources of sulfur in diesel fuel are the sulfur-containing compounds which occur naturally in crude oil.^a Depending on the source, crude oil contains anywhere from fractions of a percent of sulfur, such as less than 0.05 weight percent (500 ppm) to as much as several percent.¹ The average amount of sulfur in crude oil refined in the U.S. is about one percent.² Most of the sulfur in crude oil is in the heaviest boiling fractions. Since all of the refinery blendstocks that can be used to manufacture diesel fuel come from the heavier boiling components of crude oil, they contain substantial amounts of sulfur.

The diesel fuel produced by a given refinery is composed of one or more blendstocks from the crude oil fractionation and conversion units at the refinery. Refinery configuration and equipment, and the range and relative volumes of products manufactured (the product slate) can significantly affect the sulfur content of diesel fuel. The diagram on the following page illustrates the configuration and equipment used at a typical complex refinery in the U.S.

^a Additives that contain sulfur are sometimes intentionally added to diesel fuel. If the proposed 15 ppm cap on sulfur content is adopted, the contribution to the total sulfur content of highway diesel fuel from the use of these additives could be significant (see Section IV.D.1.).

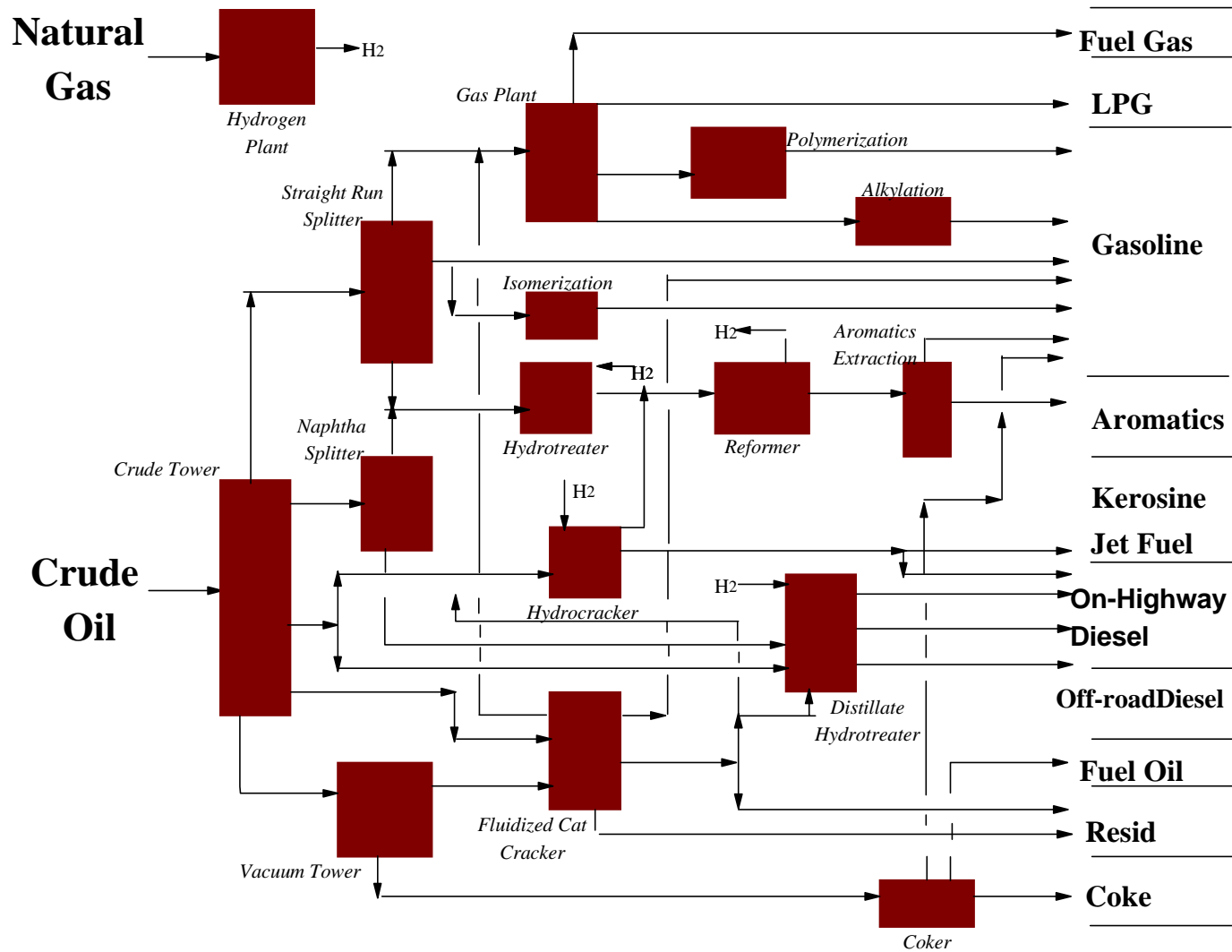


Figure IV-1: Diagram of a Typical Complex Refinery

Refineries differ from the model in the preceding diagram depending on the range of crude oils used, and their product slate. For example:

- Refiners that process heavier crudes are more likely to operate coker and/or hydrocracker units.
- Refinery streams that can be used to manufacture diesel fuel can also be used in the manufacture of heating oil, kerosene and jet fuel. Much of the distillate product from the hydrocracker is often blended into jet fuel rather than diesel fuel.

On an aggregate basis, most of the highway diesel fuel volume manufactured in the U.S. comes from the straight-run product of the crude fractionation tower (called straight run). Most of the remainder, comes from the fluid catalytic cracker (FCC) conversion unit (called light cycle oil). The remaining small fraction of diesel fuel volume comes from a coker conversion unit (called light coker gas oil), or from the hydrocracker conversion unit (called hydrocrackate).

To comply with the current federal regulatory requirement on the sulfur content of highway diesel fuel (500 ppm cap), the blendstock streams from these process units are typically further processed to reduce their sulfur content. Desulfurization of diesel blendstocks is currently accomplished in fixed-bed hydrotreaters that operate at moderate pressures (500-600 psi). Most of the low-sulfur diesel blendstocks come from such hydrotreaters. However, a small amount of low-sulfur diesel also comes from hydrocrackers. The sulfur levels of the various highway diesel blendstocks and the fraction of the total volume of highway diesel fuel that comes from each blendstock varies considerably from refinery to refinery. A recent survey conducted by the American Petroleum Institute (API) and National Petroleum Refiners Association (NPRA) in 1996 examined the typical blendstock properties for the U.S. highway diesel pool as a whole.³ The results of this survey are contained in the following tables (IV-1 and IV-2).

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**TableIV-1: Volume Fraction of U.S. Highway Diesel Pool
from each Blendstock Component⁴**

<i>Diesel Blendstock</i>	<i>Percent of U.S. Highway Diesel Fuel Pool per Blendstock Boiling Fraction</i>				
	<i>Naptha</i>	<i>Light Distillate</i>	<i>Heavy Distillate</i>	<i>Light Gas Oil</i>	<i>All Boiling Fractions Combined</i>
Straight Run	0.1	6.4	4.9	1.0	12.4
Hydrotreated Straight Run	0.3	8.1	41.2	2.3	51.9
Cracked Stock	-	0.1	0.8	2.2	3.1
Hydrotreated Cracked Stock	-	2.1	15.6	1.7	19.4
Coker Gas Oil	-	-	1.0	-	1.0
Hydrotreated Coker Gas Oil	0.1	2.1	3.7	2.3	8.2
Hydrocrackate	-	1.3	2.7	-	4.0

Table IV-2: Sulfur Levels of Highway Diesel Blendstocks (CA Excluded)⁵

Diesel Blendstock	Sulfur Content (ppm) by Boiling Fraction of the Blendstock ^{*1}				
	Naptha	Light Distillate	Heavy Distillate	Light Gas Oil	All Boiling Fractions Combined ^{*2}
Straight Run	827	1,770	2,269	4,980	2,218
Hydrotreated Straight Run	362	119	394	548	358
Cracked Stock	-	2,219	2,892	<i>6,347^{*3}</i>	5,322
Hydrotreated Cracked Stock	18	37	939	<i>1,306</i>	874
Coker Gas Oil	540	1,800	3,419	-	3,419
Hydrotreated Coker Gas Oil	8	25	310	400	258
Hydrocrackate	-	12	120	-	85

*1) The boiling ranges that define the four different boiling fractions of each diesel blendstock (naptha, light distillate, heavy distillate, and light gas oil) varied somewhat from refiner to refiner. There was also definitional overlap in the boiling ranges provided by refiners.

*2) These values were derived by weighting the values for the four boiling fractions by the fraction they represent of the highway diesel fuel blendstock (see Table IV-1).

*3) Italics indicate properties that were not reported in the refiner survey. These values were calculated using the reported sulfur contents of like boiling fractions in other diesel blendstocks by assuming the same relative sulfur levels between boiling fractions. This was necessary to allow the calculation of the sulfur content of the blendstock as a whole.

As shown in Table IV-1, approximately 80 percent of all blendstocks used to manufacture highway diesel fuel outside of California are hydrotreated to reduce their sulfur content. Hydrocrackate is desulfurized to a substantial extent as a necessary element of the hydrocracking process and is not further processed in a hydrotreater. The table also shows that approximately 16 percent of relatively high-sulfur containing blendstocks are currently blended into highway diesel fuel in limited quantities.

The blendstocks used to manufacture highway diesel fuel used in California differ from the rest of the nation due to the unique requirements of the California market and California-specific regulatory requirements that have resulted in an average sulfur content of 140 ppm for California highway diesel fuel.⁶ Highway diesel fuel used in California is made primarily from hydrocrackate and hydrotreated straight run in roughly equal proportions, with a small volume fraction of

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hydrotreated cracked stock and hydrotreated coker gas oil. No high-sulfur containing blendstocks are used in the manufacture of California highway diesel fuel. California diesel fuel requirements include a limit on aromatics content which limits the amount of light-cycle oil (LCO) and light-coker gas oil (LCGO) that can be used in the manufacture of California highway diesel fuel. LCO and LCGO have a high aromatics content which is not reduced by desulfurization.

2. Current Levels of Sulfur in Highway Diesel Fuel

To determine the most cost-effective sulfur removal methods, it is important to evaluate the amount of sulfur currently in highway diesel fuel. EPA set standards for highway diesel fuel quality in 1990 (55 FR 34120, August 21, 1990). These standards have been effective since 1993. The standards limit the sulfur concentration in fuel to a maximum of 500 ppm, compared to a pre-regulation average of 2500 ppm. They also protect against a rise in the fuel's aromatics content from then-existing levels by setting a minimum cetane index of 40 (or, alternatively, a maximum aromatics level of 35 volume percent).

California set more stringent standards in 1988 for motor vehicle diesel fuels used in the South Coast air basin.⁷ These standards took effect statewide in 1993. They apply to both highway and off-highway fuels (excluding marine and locomotive use), and limit sulfur levels to 500 ppm and aromatics levels to 10 volume percent, with some flexibility provisions to accommodate small refiners and alternative formulations. Under the provisions for alternate formulations, fuel manufacturers have certified highway diesel fuel for use on California with a lower maximum sulfur content than 500 ppm and a higher maximum aromatics content than 10 percent. Alaska and certain U.S. territories currently have an exemption from federal highway diesel fuel requirements. In these areas, the industry-established specification on the maximum allowed sulfur content of diesel fuel (5,000 ppm) applies.⁸ These regulatory and industry criteria set the upper bound on the sulfur content of highway diesel fuel in the U.S.

To enable our cost analysis, we compiled the data by various regions called Petroleum Administrative Districts for Defense (PADDs), as well as for California and the country as a whole.⁹ The PADD regions are illustrated in the following figure (IV-2).

Petroleum Administration for Defense (PAD) Districts



Figure IV-2: Map of U.S. Petroleum Administrative Districts for Defense

Our evaluation revealed relatively little difference in the sulfur content of highway diesel fuel in PADDs 1, 2, 3, and 4. The sulfur content of highway diesel fuel in California is considerably lower than that in the rest of the nation due to regulatory requirements specific to California. The sulfur content of diesel fuel in PADD 5 outside of California and Alaska, although higher than that within California, is lower than that in PADDs 1 through 4. This is due to the fact that a large fraction of the highway diesel fuel used in PADD 5 outside of California and Alaska is manufactured by refineries that are configured primarily to supply lower-sulfur diesel fuel to the California market. Alaska currently has an exemption from federal highway diesel sulfur requirements. Please refer to Chapter VII for a discussion of diesel fuel sulfur levels in Alaska.

Table IV-3: Average Highway Diesel Fuel Sulfur Levels by Geographic Area

	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5 O-CA&AK*</i>	<i>CA</i>	<i>U.S. Avg.*</i>
Sulfur Content (PPM)	340	350	360	330	280	140	340

* Outside of California and Alaska.

3. Current Levels of Other Fuel Parameters in Highway Diesel Fuel

The refinery process options which could be used reduce the sulfur content of highway diesel to the level proposed have the potential to affect other fuel parameters as well. Highway diesel fuel is required to meet specifications on a range of fuel parameters.¹⁰ If process changes made to comply with the proposed cap on sulfur content adversely affect other fuel parameters, refiners may need to take additional steps to ensure that these other parameters meet specifications. Thus, to determine the most cost-effective sulfur removal methods, it is also important to evaluate current levels of the other fuel parameters which might be affected by refinery process changes to meet the proposed sulfur cap. Data on the current distillation characteristics, API gravity, pour point, natural cetane level, and aromatics content of diesel fuel blendstocks are contained in the following tables (IV-4, IV-5, and IV-6).

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Table IV-4: Distillation Characteristics of Diesel Blendstocks (CA Excluded.)¹¹

<i>Blendstock</i>	<i>Distillation Fraction</i>	<i>Distillation (°F)</i>				
		<i>T10</i>	<i>T30</i>	<i>T50</i>	<i>T70</i>	<i>T90</i>
Straight-Run	Naptha	325	349	393	422	452
	Light Distillate	360	394	421	443	477
	Heavy Distillate	466	510	540	567	601
	Light Gas Oil	421	456	547	575	618
Hydrotreated Straight Run	Naptha	296	375	405	432	467
	Light Distillate	383	412	429	454	484
	Heavy Distillate	431	492	543	576	621
	Light Gas Oil	457	528	584	-	595
Cracked Stock	Naptha	-	-	-	-	-
	Light Distillate	346	357	369	384	408
	Heavy Distillate	488	-	526	541	637
	Light Gas Oil	-	508	547	599	666
Hydrotreated Cracked Stock	Naptha	284	-	310	-	351
	Light Distillate	345	360	385	440	508
	Heavy Distillate	448	501	-	565	613
	Light Gas Oil	457	524	534	-	634
Coker Gas Oil	Naptha	237	-	314	-	399
	Light Distillate	369	382	394	410	436
	Heavy Distillate	454	-	501	531	561
	Light Gas Oil	-	-	-	-	-
Hydrotreated Coker Gas Oil	Naptha	188	210	245	275	305
	Light Distillate	359	375	463	494	580
	Heavy Distillate	460	-	504	534	594
	Light Gas Oil	521	564	599	-	628
Hydrocrackate	Naptha	-	-	-	-	-
	Light Distillate	357	393	435	459	503

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	Heavy Distillate	433	501	528	556	617
	Light Gas Oil	-	-	-	-	-

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Table IV-5: Properties of Diesel Blendstocks (CA Excluded.)¹²

<i>Blendstock</i>	<i>Distillation Fraction</i>	<i>Aromatics (Vol %)</i>	<i>Cetane # (Unadditized)</i>	<i>API Gravity</i>	<i>Pour Point (°F)</i>
Straight-Run	Naptha	-	-	50.0	70 (additized)
	Light Distillate	15.9	40.3	42.2	-
	Heavy Distillate	15.5	-	35.2	-
	Light Gas Oil	-	45.0	30.3	11
Hydrotreated Straight Run	Naptha	-	-	47.1	-
	Light Distillate	18.6	44.5	42.9	-
	Heavy Distillate	31.0	50.4	34.4	-
	Light Gas Oil	-	-	29.9	3
Cracked Stock	Naptha	-	-	-	-
	Light Distillate	40.2	-	33.1	-
	Heavy Distillate	-	-	26.8	-
	Light Gas Oil	-	-	22.3	-
Hydrotreated Cracked Stock	Naptha	-	-	52.6	-
	Light Distillate	19.0	42.7	45.0	-
	Heavy Distillate	45.0	44.1	30.7	-
	Light Gas Oil	-	-	-	-
Coker Gas Oil	Naptha	8.0	-	51.7	-
	Light Distillate	-	-	42.4	-
	Heavy Distillate	-	-	32.2	-
	Light Gas Oil	-	-	-	-
Hydrotreated Coker Gas Oil	Naptha	-	-	-	-
	Light Distillate	22.1	45.3	43.1	-
	Heavy Distillate	25.1	-	34.8	-
	Light Gas Oil	-	36.1	29.9	-
Hydrocrackate	Naptha	-	-	-	-
	Light Distillate	-	-	41.8	-

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	Heavy Distillate	24.2	50.2	32.9	-
	Light Gas Oil	-	-	-	-

Table IV-6: Average Highway Diesel Fuel Parameter Levels by Geographic Area¹³

<i>Fuel Parameter</i>	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5 (OC)*</i>	<i>CA</i>	<i>U.S. (OC)*</i>	
API Gravity	34.6	34.2	34.3	36.2	33.8	33.6	34.4	
Cetane Number Unadditized	-	42.9	43.8	-	46.5	42.6	44.1	
Cetane Additive (ppmv)	0	83	2	12	0	183	27	
Cetane Number [additized]	-	-	-	-	-	-	-	
Pour Point (°F) [additized]	[10]	[10]	[2]	0	[2]	6	[5]	
Pour Point Depressant Additive (ppmw)	7	47	7	11	0	0	19	
Distillation (°F)	T10	426	427	436	405	432	447	431
	T30	458	470	478	435	472	-	471
	T50	497	505	514	495	521	525	510
	T70	549	549	557	519	554	-	551
	T90	609	600	610	598	611	612	606
Aromatics (Vol %)	28.9	25.8	37.0	27.1	-	28.8	32.3	

* Outside of California

4. Overview of Diesel Fuel Sulfur Control

As mentioned in Section A.1., the sulfur in diesel fuel comes from the crude oil processed by the refinery. One way to reduce the amount of sulfur in diesel fuel, therefore, is to process a crude oil that is lower in sulfur. Some refiners already do this. Others could switch to low or at least lower sulfur crude oils. However, there is limited capability worldwide to produce low sulfur crude oil. Most of the new crude oil production being brought on-line is for heavier, more sour (i.e., higher sulfur) crude oils. The incentive to use low sulfur crude oils has existed for some time and low sulfur crude oils have traditionally commanded a premium price relative to higher sulfur crude

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oils. While a few refiners with access to lower sulfur crude oil could potentially reduce their diesel sulfur levels in this way, it is not feasible for most, let alone all U.S. refiners to switch to low sulfur crude oils in order to meet a tighter diesel fuel sulfur standard. In addition, a simple change to a low sulfur crude oil would not provide compliance with the proposed 15 ppm sulfur cap. Thus, this analysis will not assume that this is a broader applicable approach to meeting the proposed standard.

Another method to reduce diesel fuel sulfur is to chemically remove sulfur from the hydrocarbon compounds which comprise diesel fuel. This is usually accomplished through reaction with hydrogen at high temperature and pressure. A couple of specific examples of this process are hydrotreating and hydrocracking. Other low temperature and pressure processes are being developed, such as biodesulfurization. Sulfur can be removed via these processes from refinery streams which are not yet ready to be blended into diesel fuel, but will be further processed in the refinery into diesel fuel (i.e., early in the refining process). Or, sulfur can be removed from those refinery streams which are to be blended directly into diesel fuel (i.e., late in the refining process).

Finally, another method to reduce diesel fuel sulfur is to shift sulfur-containing hydrocarbon compounds to other fuels produced by the refinery.

As will be shown below, we expect that most of the sulfur reduction required by the proposed sulfur cap will be chemically removed via hydrotreating. Thus, this section will begin with a relatively detailed discussion of the capabilities of this and similar processes. We also expect refiners to use the other methods to obtain cost effective sulfur reductions which will complement the primary sulfur reduction achieved via hydrotreating. These other methods, such as FCC feed hydrotreating, biodesulfurization and undercutting LCO, will be discussed following the primary discussion of distillate hydrotreating.

5. Hydrotreating and Other Hydrogen-Based Processes Which Remove Sulfur

Hydrotreating and similar processes generally combine hydrogen with a hydrocarbon stream at high temperature and pressure in the presence of a catalyst. Refineries currently employ a wide range of these processes for a number of purposes. For example, naphtha (gasoline like material which itself does not meet gasoline specifications, such as octane level) being fed to the refinery reformer is always hydrotreated to remove nearly all sulfur, nitrogen and metal contaminants which would deactivate the noble metal catalyst used in the reforming process. Similarly, feed to the FCC unit is often hydrotreated to remove most of the sulfur, nitrogen and metal contaminants in order to improve the yield and quality of high value products, such as gasoline and distillate. (Distillate refers to a range of similar products including kerosene, diesel fuel, No. 2 heating oil and jet fuel.) Nearly all refineries currently hydrotreat the refinery streams used to produce highway diesel fuel in order to remove much of the sulfur present and comply with the current 500 ppm sulfur cap. EPA

expects that nearly all refiners will hydrotreat the naphtha produced by the FCC unit in order to remove most of the sulfur present and comply with the just promulgated gasoline sulfur standards.¹⁴ These hydrotreating processes remove sulfur, nitrogen, metal and other contaminants from the hydrocarbon streams. They also generally saturate any olefins present. However, they do not generally otherwise affect the chemical nature of the hydrocarbon themselves.

If the temperature or pressure is increased sufficiently, or a carbon-oriented catalyst is used, hydrotreating can more dramatically affect the chemical nature of the hydrocarbons, as well as remove contaminants. For example, through a process called hydrocracking, smaller, lighter molecules are created by splitting larger, heavier molecules. In the process, nearly all of the contaminants are removed and olefins and aromatics are saturated into paraffins. Outside of the U.S., this process is commonly used to produce distillate from heavier, less marketable refinery streams. The production of distillate via hydrocracking is less common in the U.S. However, a number of U.S. refiners also use hydrocracking to produce gasoline from poor quality distillate, such as LCO from the FCC unit.

A few refineries also currently hydrotreat their distillate more severely than is typical, but not as severe as hydrocracking. Their intent is to remove the sulfur, nitrogen and metallic contaminants and to also saturate most of the aromatics present. This is done primarily in Europe to meet very stringent specifications for both sulfur and aromatics applicable to certain diesel fuels and encouraged by reduced excise taxes. A different catalyst which encourages aromatic saturation is used in lieu of one that simply encourages contaminant removal.

In order to meet the proposed sulfur cap, EPA expects refiners to focus as much as possible on just sulfur removal. Other contaminants, such as nitrogen and metals, are already sufficiently removed by existing refinery processes. While saturation of aromatics generally improves diesel fuel quality, there is an additional cost involved, primarily the consumption of additional hydrogen. Consequently, we anticipate refiners will choose desulfurization processes that minimize the amount of aromatics saturation. Current diesel fuel already meets all applicable specifications, and hydrotreating to remove sulfur should not degrade quality, except possibly lubricity. Thus, with this one exception, there should be no need to improve diesel fuel quality as a direct result of this proposed regulation. Should a refiner choose to do so, it would be for market reasons and not related to meeting the proposed sulfur cap. More severe processes will only be considered when hydrotreating for sulfur removal (desulfurization) is projected to be insufficient to meet the proposed sulfur cap.

As mentioned above, this sulfur removal can occur either early or late in the refining process. The most practical place to remove sulfur early in the process is prior to the FCC unit. Hydrotreating feed to the FCC unit requires higher temperatures and pressures than hydrotreating distillate streams used to produce diesel fuel because FCC feed contains much larger and heavier molecules. Because of this, FCC feed hydrotreating is more expensive than distillate hydrotreating. We expect that most refiners will enhance or expand their current distillate hydrotreating capability to meet the proposed sulfur cap, although the other benefits associated with FCC feed hydrotreating

could lead some refiners to add this technology. The remaining discussion of hydrotreating will therefore begin with distillate hydrotreating, followed by a more brief discussion of FCC feed hydrotreating.

a. Fundamentals of Distillate Hydrotreating

Essentially all distillate hydrotreater designs follow the same broad format. Liquid distillate is heated and pumped to temperatures of 300-380°C and pressures of 300-900 psia with hydrogen and reacted over a catalyst. Hydrogen reacts with sulfur and nitrogen atoms contained in the hydrocarbon molecules, forming hydrogen sulfide and ammonia. The resulting vapor is then separated from the desulfurized distillate. The desulfurized distillate is usually simply mixed with other distillate streams in the refinery to produce diesel fuel and heating oil.

The vapor still contains a lot of valuable hydrogen, because the reaction requires the use of a significant amount of excess hydrogen to operate efficiently and practically. However, the vapor also contains a significant amount of hydrogen sulfide and ammonia, which inhibit the desulfurization and denitrogenation reactions and must be removed from the system. Thus, the hydrogen leaving the reactor is usually mixed with fresh hydrogen and recycled to the front of the reactor for reaction with fresh distillate feed. However, by itself, this would cause a build up of hydrogen sulfide and ammonia in the system, since it would have no way to leave the system. In some cases, the hydrogen sulfide and ammonia are chemically scrubbed from the hydrogen recycle stream. In other cases, some of the recycle stream is simply purged from the system as a mixture of hydrogen, hydrogen sulfide and ammonia. The latter is less efficient since it leads to higher levels of hydrogen sulfide and ammonia in the reactor, but it avoids the cost of building and operating a scrubber.

Desulfurization processes in-use today in the U.S. generally use only one reactor, due to the need to only desulfurize diesel fuel to 500 ppm or lower. However, a second reactor can be used, particularly to meet lower sulfur levels. Instead of liquid distillate going to the diesel fuel/heating oil pool after the first reactor, it would simply be reheated, mixed with fresh hydrogen and sent to the second reactor.

Traditional reactors are cocurrent in nature. The hydrogen is mixed together with the distillate at the entrance to the reactor and flow through the reactor together. Because the reaction is exothermic, heat must be removed periodically. This is sometimes done through the introduction of fresh hydrogen and distillate at one or two points further down the reactor. The advantage of cocurrent design is practical, it eases the control of gas-liquid mixing and contact with the catalyst. The disadvantage is that the concentration of hydrogen is the highest at the front of the reactor and lowest at the outlet. The opposite is true for the concentration of hydrogen sulfide. This increases the difficulty of achieving extremely low sulfur levels due to the low hydrogen concentration and high hydrogen sulfide concentration at the end of the reactor.

The normal solution to this problem is to design a counter-current reactor, where the fresh

hydrogen is introduced at one end of the reactor and the liquid distillate at the other end. Here, the hydrogen concentration is highest (and the hydrogen sulfide concentration is lowest) where the reactor is trying to desulfurize the most difficult (sterically hindered) compounds. The difficulty of counter-current designs in the case of distillate hydrotreating is vapor-liquid contact and the prevention of hot spots within the reactor. The SynAlliance (consisting of ABB Lummus, Criterion Catalyst Corp., and Shell Oil Co.) has patented a counter-current reactor design called SynTechnology. With this technology, in a single reactor design, the initial portion of the reactor will follow a co-current design, while the last portion of the reactor will be counter-current. In a two reactor design, the first reactor will be co-current, while the second reactor will be counter-current.

ABB Lummus estimates that the counter-current design can reduce the catalyst volume needed to achieve 97 percent desulfurization by 16 percent relative to a co-current design.¹⁵ The impact of the counter-current design is even more significant when aromatics control (or cetane improvement) is desired in addition to sulfur control.

Sulfur containing compounds in distillate can be classified according to the ease with which they are desulfurized. Sulfur contained in paraffins or aromatics with a single aromatic ring are relatively easy to desulfurize. These molecules are sufficiently flexible so that the sulfur atom is in a geometric position where it can make physical contact with the surface of the catalyst. The more difficult compounds are contained in aromatics consisting of two aromatic rings, particularly dibenzothiophenes. Dibenzothiophene contains two benzene rings which are connected by a carbon-carbon bond and two carbon-sulfur bonds (both benzene rings are bonded to the same sulfur atom). This compound is essentially flat in nature and the carbon atoms bound to the sulfur atom hinder the approach of the sulfur atom to the catalyst surface. Despite this, today's catalysts are very effective in desulfurizing dibenzothiophenes, as long as only hydrogen is attached to the carbon atoms bound directly to the sulfur atom.

However, distillate can contain dibenzothiophenes which have methyl or ethyl groups bound to the carbon atoms which are in turn bound to the sulfur atom. These extra methyl or ethyl groups further hinder the approach of the sulfur atom to the catalyst surface. Dibenzothiophenes with such methyl or ethyl groups are commonly referred to as being sterically hindered. An example of a dibenzothiophene with a single methyl or ethyl group next to the sulfur atom is 4-methyl dibenzothiophene. An example of a dibenzothiophene with two methyl or ethyl groups next to the sulfur atom is 4,6-dimethyl dibenzothiophene. In 4,6-dimethyl dibenzothiophene, and similar compounds, the presence of a methyl group on either side of the sulfur atom makes it very difficult for the sulfur atom to react with the catalyst surface to assist the hydrogenation of the sulfur atom.

Straight run distillate (or straight run gas oil (SRGO)) contains relatively low levels of these sterically hindered compounds. LCO, contains the greatest concentration of sterically hindered compounds. Thus, LCO is generally more difficult to desulfurize than straight run distillate.¹⁶ In addition, cracked stocks, particularly LCO, have a greater tendency to form coke on the catalyst, which deactivates the catalyst and requires its replacement.

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The greater presence of sterically hindered compounds in LCO is related to two fundamental factors. First, LCO contains much higher concentrations of aromatics than typical SRGO.¹⁷ All sterically hindered compounds are aromatics. Second, the chemical equilibria existing in cracking reactions favors the production of sterically hindered dibenzothiophenes over unsubstituted dibenzothiophenes. For example, in LCO, methyl substituted aromatics are twice as prevalent as unsubstituted aromatics. Di-methyl aromatics are twice as prevalent as methyl aromatics, or four times more prevalent as unsubstituted aromatics. Generally, desulfurizing 4-methyl dibenzothiophene is 6 times slower than desulfurizing similar non-sterically hindered molecules, while desulfurizing 4,6-dimethyl dibenzothiophene is 30 times slower. Slower reactions mean that either the volume of the reactor must be that much larger, or that the reaction must be somehow speeded up. The latter implies either a more active catalyst, higher temperature, or higher pressure. These alternatives will be discussed later below.

Because moderate sulfur reduction is often all that is required in distillate hydrotreating, catalysts have been developed which focus almost exclusively on contaminant removal. The most commonly used desulfurization catalyst consists of a mixture of cobalt and molybdenum (Co/Mo). These catalysts interact primarily with the sulfur atom and encourage the reaction of sulfur with hydrogen.

Other catalysts have been developed which encourage the saturation (hydrogenation) of the aromatic rings. As mentioned above, this generally improves the quality of the diesel fuel produced from this distillate. These catalysts also indirectly encourage the removal of sulfur from sterically hindered compounds by eliminating one or both of the aromatic rings contained in dibenzothiophene. Without one or both of the rings, the molecule is much more flexible and the sulfur atom can approach the catalyst surface much more easily. The most commonly used dehydrogenation/desulfurization catalyst consists of a mixture of nickel and molybdenum (Ni/Mo).

Up to a certain level of sulfur removal, the CoMo catalyst is generally preferred. It is more active with respect to desulfurizing non-sterically hindered compounds, which comprise the bulk of the sulfur in distillate, straight run or cracked. Below that level, the need to desulfurize sterically hindered compounds leads to greater interest in NiMo catalysts. Acreon Catalysts had indicated that NiMo are preferred for deep desulfurization around 15 ppm due to this catalyst's ability to saturate aromatic rings and make the sulfur atom more accessible to the catalyst. On the other hand, Haldor-Topsoe has performed studies which indicate that CoMo catalysts may still have an advantage over NiMo catalysts, even at sulfur levels below 50 ppm.¹⁸

Two-stage processes may also be preferable to achieve ultra-low sulfur levels. Both stages could emphasize desulfurization or desulfurization could be emphasized in the first stage and hydrogenation/desulfurization emphasized in the second stage. In either case, the advantage of two stages lies in the removal of hydrogen sulfide from the gas phase after the first stage. Hydrogen sulfide strongly inhibits desulfurization reactions, as will be discussed further in the next section. It can also recombine with non-sulfur containing hydrocarbon compounds at the end of the reactor or even in subsequent piping, essentially adding sulfur to the desulfurized distillate. Removing

hydrogen sulfide after the first stage reduces the hydrogen sulfide concentration at the end of the second stage by roughly two orders of magnitude, dramatically reducing both inhibition and recombination.

In one study, Haldor-Topsoe analyzed a specific desulfurized 50/50 blend of SRGO and LCO at 150 ppm sulfur and found that essentially all of the sulfur is contained in sterically hindered compounds.¹⁹ This feed contains more LCO than would be processed in the typical refinery. A refinery processing less LCO would presumably reach the point where the sulfur compounds were dominated by sterically hindered compounds at a lower sulfur level. They also compared the performance of CoMo and NiMo catalysts on a SRGO feed at the same space velocity. The NiMo catalyst performed more poorly than the CoMo catalyst above 200 ppm sulfur, and better below that level. This implies that much of the sulfur left at 200 ppm (and even above this level) was sterically hindered. These two studies indicate that the amount of sterically hindered compounds can exceed the proposed 15 ppm sulfur cap by a substantial margin.

In addition to NiMo catalysts, precious metal catalysts are also very effective in removing sterically hindered compounds. They are most commonly used to more severely dearomatize distillate and increase cetane. An example of a precious metal catalyst is the ASAT catalyst developed by United Catalysts and Sud-Chemie AG, which uses both platinum and palladium.²⁰

b. Meeting a 15 ppm Cap with Distillate Hydrotreating

Using distillate hydrotreating to meet a 15 ppm sulfur cap on highway diesel fuel has been commercially demonstrated, as will be discussed below. Thus, meeting the proposed 15 ppm cap is quite feasible using current refining technology. Assessing the most economic means of doing so is more complicated. Refiners already hydrotreat their highway diesel fuel to meet a 500 ppm sulfur cap. These hydrotreaters use a variety of catalysts and have a range of excess capacity. Thus, refiners are not all starting from the same place. Many refiners also produce off-highway diesel fuel and heating oil, which have much less stringent sulfur requirements and could, for example, provide a sink for sterically hindered sulfur containing compounds. Finally, the amount of cracked stocks that a refiner processes into diesel fuel varies widely. Those with a greater fraction of LCO will face a more difficult task of complying with a 15 ppm cap, than those processing primarily SRGO.

In addition to a range of initial conditions faced by refiners, refiners also have a choice of continuing to use their existing distillate hydrotreater or to scrap that equipment and design an entirely new hydrotreater. As will be shown below, numerous commercial examples exist where existing hydrotreaters have been modified to improve their sulfur removal performance. Thus, we project that all refiners with distillate hydrotreaters will continue to use this equipment and their first step in complying with the proposed sulfur cap will be to improve the performance of this equipment as much as possible.

In order to understand the types of modifications which can be made to distillate hydrotreaters in order to improve their performance, it is useful to better understand the quantitative

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relationships between the various physical and chemical parameters involved in hydrotreating. Haldor-Topsoe has developed the following algebraic expression to describe the rate of desulfurization via both direct desulfurization and hydrogenation/desulfurization.

$$\begin{array}{l} \text{Rate of} \\ \text{Desulfurization} \\ \text{Per Catalyst} \\ \text{Surface Area} \end{array} = \frac{k * C_s^n * P_{H_2}^a}{(1 + K_{H_2S} * P_{H_2S})} + \frac{k * C_s^m * P_{H_2}^b}{(1 + K_F * C_F)}$$

where: k , K_{H_2S} and K_F are various rate constants, which only vary with temperature
 C_s is the concentration of sulfur in the distillate
 P_{H_2} and P_{H_2S} are the partial pressures of hydrogen and hydrogen sulfide in the vapor phase
 $K_F * C_F$ is the total inhibition due to hydrogen sulfide, ammonia, and aromatics
 n , m , a , and b are various constant exponents

The first term represents the rate of direct desulfurization, such as that catalyzed by CoMo. This reaction rate increased by increasing the partial pressure of hydrogen. However, it is inhibited by increasing concentrations of hydrogen sulfide, which competes with the distillate for sites on the catalyst surface.

The second term represents the rate of desulfurization via hydrogenation of the aromatic ring next to the sulfur atom. This rate of desulfurization also increases with higher hydrogen partial pressure. However, this reaction is inhibited by hydrogen sulfide, ammonia, and aromatics. This inhibition by aromatics leads to the presence of a thermodynamic equilibrium condition which can prevent the complete saturation of aromatics. Also, this inhibition makes it more difficult to desulfurize cracked stocks, which contain high concentrations of both sterically hindered sulfur compounds and aromatics. While the literature generally expresses a preference for NiMo catalysts for desulfurizing cracked stocks, Haldor-Topsoe has found situations where this aromatics inhibition leads them to favor CoMo catalysts even for desulfurizing feeds with a high concentration of sterically hindered compounds.

These relationships essentially identify the types of changes which could be made to improve the performance of current distillate hydrotreaters. First, a more active catalyst can be used. This increases the “ k ” terms in the above equations. Second, temperature can be increased, which increases the “ k ” terms in the above equations. Third, improvements can often be made in vapor-liquid contact, which effectively increases the surface area of the catalyst. Fourth, hydrogen purity can be increased. This increases the P_{H_2} term in the two numerator terms of the equation. Fifth, the concentration of hydrogen sulfide in the recycle stream can be removed by scrubbing. This decreases the P_{H_2S} and C_F terms in the two denominator terms of the equation. Finally, more volume of catalyst can be used, which increases the surface area proportionally.

Regarding catalysts, at least two firms have announced the development of improved

catalysts since the time that most distillate hydrotreaters were built in the U.S. to meet the 1993 500 ppm sulfur cap: Akzo Nobel / Nippon Ketjen Catalysts (Akzo Nobel) and Haldor-Topsoe. Akzo Nobel currently markets 3 CoMo desulfurization catalysts: KF 752, KF 756 and KF 757. KF 752 can be considered to be typical of an Akzo Nobel catalyst of the 1992-93 timeframe, while KF 756 and 757 catalysts represent improvements. Akzo Nobel estimates that under typical conditions (e.g., 500 ppm sulfur), KF 756 is 25 percent more active than KF 752, while KF 757 is more than 50 percent more active than KF 752 and 30 percent more active than KF 756.²¹ However, under more severe conditions (e.g., <50 ppm sulfur), KF 757 is 35-75 percent more active than KF 756. Commercial experience exists for both advanced catalysts. KF 756 is widely used in Europe (20 percent of all distillate hydrotreaters operating on January 1, 1998), while KF 757 has been used in at least three hydrotreaters commercially. KF 757 utilizes what Akzo Nobel calls STARS technology, Super Type II Active Reaction Sites. Type II refers to a specific kind of catalyst site which is particular good at removing sulfur from sterically hindered compounds.

In terms of sulfur removal, Akzo Nobel projects that a desulfurization unit producing 500 ppm sulfur with KF 752, would produce 405 and 270 ppm sulfur with KF 756 and KF757, respectively.

Haldor-Topsoe has also developed a more active catalyst. Its TK-554 catalyst is analogous to Akzo Nobel's KF 756 catalyst, while its newer, more active catalyst is termed TK-574. For example, in pilot plant studies, under conditions where TK-554 produces 400 ppm sulfur in SRGO, TK 574 will produce 280 ppm. Under more severe conditions, TK-554 will produce 60 ppm, while TK 574 will produce 30 ppm. Similar benefits are found with a mixture of straight run and cracked stocks.

UOP projects a similar reduction in sulfur due to improved catalyst. They estimate that a hydrotreater producing 500 ppm sulfur distillate today (20% LCO, 10% light coker gas oil) could produce 280 ppm sulfur distillate with a 50% more active catalyst.²²

Thus, by itself, changing to a more active catalyst can reduce sulfur moderately. Based on the history of the industry, improvements in catalyst performance can be anticipated over time to result in roughly a 25 percent increase in catalyst activity every 4 years. Vendors have informed EPA that the cost of these advanced catalysts is very modest relative to less active catalysts. This will help to reduce the reactor size needed, but by itself would not appear to be sufficient for most refiners to meet a 15 ppm cap.

The second type of improvement is to reduce the concentration of hydrogen sulfide, which reduces the inhibition of the desulfurization and hydrogenation reactions. Hydrogen sulfide can be removed by chemical scrubbing. Haldor-Topsoe indicates that decreasing the concentration of hydrogen sulfide at the inlet to a co-current reactor by three to six volume percent can decrease the average temperature needed to achieve a specific sulfur reduction by 15-20°C, or reduce final sulfur levels by more than two-thirds. UOP projects that scrubbing hydrogen sulfide from recycle hydrogen can reduce sulfur levels from roughly 285 to 180 ppm in an existing hydrotreater.

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The third type of improvement which can be made to current distillate hydrotreaters is to improve vapor-liquid contact. Akzo Nobel estimates that an improved vapor-liquid distributor can reduce the temperature necessary to meet a 50 ppm sulfur level by 10 °C, which in turn would increase catalyst life and allow an increase in cycle length from 10 to 18 months. Based on the above data from Haldor-Topsoe, if temperature were maintained, the final sulfur level could be reduced by 50 percent. Similarly, in testing of an improved vapor-liquid distributor in commercial use, Haldor-Topsoe found that the new distributor allowed a 30 percent higher sulfur feed to be processed at 25°C lower temperatures, while reducing the sulfur content of the product from 500 to 350 ppm. Maintaining temperature should have allowed an additional reduction in sulfur of more than two-thirds. Thus, ensuring adequate vapor-liquid contact can have a major impact on final sulfur levels.

The fourth improvement possible is to increase hydrogen partial pressure and/or purity. As discussed above, this increases the rate of both desulfurization and hydrogenation reactions. Haldor-Topsoe indicates that increasing hydrogen purity is preferable to a simple increase in the pressure of the hydrogen feed gas, since the latter will also increase the partial pressure of hydrogen sulfide later in the process, which inhibits both beneficial reactions. Haldor-Topsoe projects that an increase in hydrogen purity of 30 percent would lower the temperature needed to achieve the same sulfur removal rate by eight to nine °C. Or temperature could be maintained while increasing the amount of sulfur removed by roughly 40 percent. Hydrogen purity can be increased through the use of a membrane separation system or a PSA unit. UOP projects that purifying hydrogen can reduce distillate sulfur from 180 to 140 ppm from an existing hydrotreater.

The fifth type of improvement is to increase reactor temperature. Haldor-Topsoe has shown that an increase of 14°C while processing a mix of SRGO and LCO with its advanced TK-574 CoMo catalyst will reduce sulfur from 120 ppm to 40 ppm.²³ The downside of increased temperature is reduced catalyst life (i.e., the need to change catalyst more frequently). This increases the cost of catalyst, as well as affects highway diesel fuel production while the unit is down for the catalyst change. Still, current catalyst life currently ranges from six to 24 months, so some refiners could increase temperature and still remain well within the range of current industry performance. The relationship between temperature and life of a catalyst is a primary criterion affecting its marketability. Thus, catalyst suppliers generally do not publish these figures. UOP projects that a 20 °F increase in reactor temperature would decrease sulfur from 140 to 120 ppm.

Sixth, additional sulfur can be removed by increasing the amount of recycle gas sent to the inlet of the reactor. However, the effect is relatively small. Haldor-Topsoe indicates that a 50 percent increase in the ratio of total gas/liquid ratio only decreases the necessary reactor temperature by six to eight °C. Or, temperature can be maintained and the final sulfur level reduced by 35-45 percent.

Seventh, reactor volume can be increased. UOP projects that adding doubling reactor volume would reduce sulfur from 120 to 30 ppm.

Finally, a complete second stage can be added to the existing, one-stage hydrotreater. This second stage would consist of a second reactor, a hydrogen sulfide scrubber between the first and second reactor and an additional hot stripper for the effluent of the second reactor. The compressor would also be upgraded to allow a higher pressure to be used in the new second reactor. Assuming use of the most active catalysts available in both reactors, UOP projects that converting from a one-stage to a two-stage hydrotreater could produce 5 ppm sulfur relative to a current level of 500 ppm today.

The individual improvements described cannot be simply combined, either additively or multiplicatively. As mentioned earlier, each existing distillate hydrotreater is unique in its combination of design, catalyst, feedstock, and operating conditions. While the improvements described above are probably indicative of improvements which can be made in many cases, it is not likely that all of the improvements mentioned are applicable to any one unit, or the degree of improvement may not be as great as that indicated.

In addition to these major technological options, most refiners would also have to add other more minor units to support the new desulfurization unit. These units could include hydrogen plants, sulfur recovery plants, amine plants and sour water scrubbing facilities. All of these units are already operating in refineries but may have to be expanded or enlarged.

Overall, Akzo-Nobel projects that current hydrotreaters can be modified short of a revamp to achieve 50 ppm sulfur. Acreon/IFP/Procatalyse is less optimistic, believing that more than a catalyst change will be necessary to meet this sulfur level.²⁴ BP-Amoco projects that a 70 percent improvement in catalyst activity could reduce sulfur from a current hydrotreater meeting a 500 ppm sulfur specification to 30 ppm.²⁵ While this improvement is somewhat greater than the 50 percent improvement measured by Akzo Nobel at current desulfurization severity, it indicates that it may be possible to improve current hydrotreaters to produce distillate sulfur levels in the 50-100 ppm range. Thus, it appears that additional reductions needed to meet a 15 ppm cap would require additional measures. To assess the degree that these measures would be needed, it is useful to examine the commercial and pilot plant performance of distillate hydrotreaters to achieve very low sulfur levels.

c. Low Sulfur Performance of Distillate Hydrotreating

Data from both pilot plant studies and commercial performance are available which indicate the capability of various hydrotreating technologies to reduce distillate sulfur levels to very low levels. While many studies are available which focus on reducing sulfur to 500 ppm or below, studies of achieving lower sulfur levels (e.g., 10-50 ppm) also focus on reducing aromatics content significantly. This combination is related to the fact that Swedish Class II diesel fuel must meet a tight aromatics specification in 2005 along with a 10 ppm sulfur cap.

Reducing aromatic content along with sulfur content is generally desirable with respect to diesel fuel quality, as aromatic reductions increase cetane levels and generally improve combustion characteristics. However, reducing aromatics consumes hydrogen and increases the cost of

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desulfurization relative to a case where only sulfur was being removed. A number of catalyst and engineering firms have projected the technology necessary to just reduce sulfur without a mandated aromatics reduction (and its cost) for EPA, the Engine Manufacturers Association, the American Petroleum Institute, the National Petroleum Council and others. These projections will be discussed in the next chapter on the economic impacts of this proposed rule. The discussion in this chapter will focus on the available pilot plant and commercial data demonstrating the achievement of low sulfur levels. It is worth noting that until the recent announcements by the German government to seek sulfur levels as low as 10 ppm, there had been little effort by industry to develop technology capable such a level across the diesel pool.

Recent advancements by catalyst manufacturers demonstrating the feasibility of these levels should be considered a first-generation of technology, with new and continual advancements expected over time.

Starting with SynTechnology, as of August 2, 1999, there were 24 units either in operation or in the process of being constructed. Their purposes range from desulfurization to desulfurization plus dearomatization to mild hydrocracking. Of particular interest here is a revamp of an existing two reactor distillate hydrotreater at the Lyondell / Citgo refinery in Texas.

The revamped unit was designed to process a feed very heavily weighted towards cracked material (65-70 percent LCO and LCGO). One existing reactor was converted to SynSat Technology, while the other was used simply as a flash drum. A new first-stage reactor was added. Both reactors were designed to operate in a co-current fashion. Pilot plant studies predicted average sulfur and aromatics levels of seven ppm and 31 volume percent, respectively, based on feed sulfur and aromatics levels of 11,900 ppm and 53 volume percent, respectively. The unit exceeded expectations in the case of sulfur, producing an average sulfur level of less than five ppm from a feed sulfur level of 13,800 ppm. The actual aromatic level achieved was above the target by four volume percent, but the feed aromatic level was five volume percent higher than expected. Thus, the net reduction in aromatic content in terms of volume percent was still higher than found in the pilot plant. ABB Lummus and Criterion indicate that their catalyst technology is sufficiently flexible to focus on the deep desulfurization with or without the significant aromatics reduction seen here. This is reflected in their projection of the technology needed to meet a 15 ppm sulfur cap which is discussed in the next chapter.

While this two-stage unit initially produced less than 5 ppm product, it does not do so consistently. The primary purpose of the unit is to increase cetane so that the product can be blended directly into diesel fuel. The primary sulfur reduction requirement is to protect the noble metal catalyst in the second stage reactor. This generally requires that the product from the first stage be less than 50 ppm. Thus, if the cetane specifications are being met at less severe conditions, there is no incentive to reduce sulfur any further than necessary for catalyst protection.

IFP, in conjunction with various catalyst manufacturers, offers its Prime D technology for deep desulfurization, aromatics saturation and cetane improvement.²⁶ Using a NiMo catalyst, IFP's Prime D process can produce distillate sulfur levels of 10 ppm from SRGO and of less than 20 ppm

from distillate containing 20-100 percent cracked material using a single stage reactor. With a two-stage process, less than one ppm sulfur can be achieved.

United Catalysts and Sud-Chemie AG have published data on the performance of their ASAT catalyst, which uses platinum and palladium.²⁷ The focus of their study was to reduce aromatics to less than 10 volume percent starting with a feed distillate containing up to 500 ppm sulfur and at least 100 ppm nitrogen. Starting with a feed distillate containing 400 ppm sulfur and 127 ppm nitrogen and 42.5 volume percent aromatics, the ASAT catalyst was able to reduce sulfur to eight to nine ppm, essentially eliminate nitrogen and reduce aromatics to two to five volume percent. Hydrogen consumption was 800-971 standard cubic feet per barrel (SCFB).

These studies indicate the commercial feasibility of producing diesel fuel with 10 ppm sulfur or less. The primary issue remaining is whether the degree of desulfurization necessary to meet the proposed 15 ppm cap requires the saturation of much of the aromatics in diesel fuel. This could depend on the amount of cracked stocks that the refiner blends into diesel fuel and the possibility of shifting some of the sterically hindered compounds to fuels complying with less stringent sulfur standards, such as off-highway diesel fuel and heating oil. This will be discussed next.

d. Undercutting Cracked Stocks

The primary stumbling block preventing the simple desulfurization of distillate to sulfur levels meeting the proposed 15 ppm cap is the presence of sterically hindered compounds, particularly those with two methyl or ethyl groups blocking the sulfur atom. These compounds are aromatic in nature, and are found in greatest concentration in LCO, which itself is highly aromatic. These compounds can be desulfurized readily if saturated. However, due to the much higher hydrogen cost of doing so, it is better economically if this can be avoided. Because these compounds are inherently large in molecular weight due to their chemical structure, they distill near the high end of the diesel range of distillation temperatures. Thus, it is possible to segregate these compounds from the rest of the cracked stocks via distillation and avoid the need to desulfurize them.

Once separated, this LCO material could be mixed into the refinery streams currently being used to produce off-highway diesel fuel and heating oil. These fuels would still have to meet applicable quality specifications, such as cetane, density, sulfur and distillation. For example, the industry specification for non-road diesel fuel is a minimum of 40 cetane number, and a maximum sulfur concentration of 5,000 ppm.²⁸ An analysis of off-highway diesel fuel shows that off-highway diesel fuel averages 44.4 cetane number, 3,300 ppm sulfur, 34.5 API gravity, T10 of 438 °F, T50 of 517 °F, and T90 of 600 °F.²⁹ We anticipate that refiners would need to use cetane additives to compensate for the addition of LCO in order to maintain off-highway fuel cetane levels similar to those of current in-use fuels (see Section V). Additional cold-flow additives might also be necessary for off-highway diesel fuel in the winter to maintain cold-flow performance at current levels. We anticipate that refiners would allow other off-highway and heating oil properties to change as a result of the addition of LCO, while continuing to ensure that all specifications on these

fuels are met.

Shifting LCO to off-highway diesel fuel and heating oil would prevent the need to desulfurize a sizeable fraction of the sterically hindered compounds currently present in highway diesel fuel. For example, Akzo Nobel studies indicate that a drop of 10 °C in the 95th percentile distillation point (T95) of diesel fuel decreases sulfur by 50-60 ppm.³⁰ Of course, such a shift to non-highway diesel fuel markets would decrease the amount of highway diesel fuel produced, if more easy to hydrotreat material was not switched from non-highway diesel fuels to the highway diesel fuel pool. A decrease of T95 of this magnitude effected by undercutting only LCO would decrease sulfur even more because the sulfur levels in the heaviest portions of LCO are much greater than those in SRGO and are the most difficult to desulfurize. Shifting only heavy LCO would increase the sulfur reduction per volume of highway diesel fuel lost, but would still result in a net loss of highway diesel fuel production if no other feedstocks replaced it.

While this heavy LCO material could be shifted to other markets, this does not necessarily have to be the case. Under certain conditions, this material can be recycled to the FCC unit.³¹ For this to be feasible, the refiner must hydrotreat the FCC feed at a pressure sufficient to desulfurize the sterically hindered sulfur containing compounds and the feed hydrotreater must have sufficient excess capacity to handle the additional material. This material could also be sent to an existing hydrocracker, if sufficient capacity existed, and converted into gasoline blendstock. Or, it could be hydrotreated separately under more severe conditions to remove the sulfur, such as with SynAlliance's SynShift process. This would entail higher hydrogen consumption per barrel of treated material because of some aromatic saturation. However, the amount of material being processed would be small, so overall hydrogen consumption would still be low.

A number of vendors of distillate desulfurization processes recently developed specific projections of the technology needed to meet a range of highway diesel fuel sulfur levels. These projections were developed to support refining cost studies conducted by the Engine Manufacturers Association and the American Petroleum Institute, and the National Petroleum Council.^b These projections addressed compliance with three different average sulfur levels: 10, 30 and 100 ppm. Generally, these projections indicate that it will be possible for most refineries to meet the 10 ppm average sulfur level without resorting to catalysts and operating conditions which reduce aromatic levels dramatically. Thus, it appears that the cost of providing sufficient hydrogen to saturate these aromatics can be avoided. The specifics of these projections will be addressed in more detail in the next chapter.

6. Biodesulfurization

Biodesulfurization is essentially an alternative to distillate hydrotreating. This process is being developed by Energy Biosystems. It involves the removal of sulfur from distillate or naphtha

^b See Chapter V for additional discussion on these projections.

streams using anaerobic bacteria. The distillate stream is first mixed with an aqueous media containing the bacteria, caustic soda and nutrients for the bacteria. Enzymes in the bacteria first oxidize the sulfur atoms and then cleaves some of the sulfur-carbon bonds. The sulfur leaves the process in the form of hydroxyphenyl benzene sulfinate, which can be used commercially as a feedstock to produce surfactants. Designs based on pilot plant studies combine biodesulfurization with conventional hydrotreating to produce diesel fuel containing 50 ppm sulfur.

7. FCC Feed Hydrotreating

At the beginning of Section 3., it was mentioned that sulfur could be removed from distillate material early or late in the refining process. Early in the process, the most practical place to remove sulfur early in the process is prior to the FCC unit. The FCC unit primarily produces gasoline, but it also produces a significant quantity of distillate, called LCO as described in Section A.1 above. LCO is high in aromatics and sulfur and contains a relatively high fraction of the sterically hindered sulfur compounds found in diesel fuel.

Many refineries already have an FCC feed hydrotreating unit. The LCO from these refineries should contain a much lower concentration of sterically hindered compounds than refineries not hydrotreating their FCC feed. Adding an FCC feed hydrotreating is much more costly than distillate hydrotreating. Just on the basis of sulfur removal, FCC feed hydrotreating is more costly than distillate hydrotreating, even considering the need to reduce gasoline sulfur concentrations, as well. This is partly due to the fact that FCC feed hydrotreating by itself is generally not capable of reducing the level of diesel fuel sulfur to those being considered in this rule. However, FCC feed hydrotreating provides other environmental and economic benefits. FCC feed hydrotreating decreases the sulfur content of gasoline significantly, as well as reducing sulfur oxide emissions from the FCC unit. Economically, it increases the yield of relatively high value gasoline and LPG from the FCC unit and reduces the formation of coke on the FCC catalyst. For individual refiners, these additional benefits may offset enough of the cost of FCC hydrotreating to make it a more economical than distillate hydrotreating. However, these benefits are difficult to estimate in a nationwide study such as this. Thus, this study will rely on distillate hydrotreating as the primary means with which refiners would meet the 15 ppm sulfur cap. For those refiners who would choose FCC feed hydrotreating, their costs would be presumably lower than distillate hydrotreating and the costs estimated in the next chapter can then be considered to be somewhat conservative in this respect.

8. Economic Issues Associated with the Supply of Highway Diesel Fuel

Concerns have also been raised with respect to the refining industry's ability to raise the capital necessary to make the refinery modifications necessary for diesel fuel, while at the same time doing so for gasoline. This has led to concerns that some refiners may refrain from investing to continue to produce highway diesel fuel, which could cause a shortage when the program is implemented. As discussed in Section IV.B. below, we have designed these programs in a manner which will serve to maximize refiner flexibility and minimize costs. Furthermore, as discussed in Section V of this draft RIA, we believe that despite the capital cost of desulfurizing their highway diesel fuel, other options for marketing the distillate streams from their refineries will be limited, and they will make the capital investment. Finally, as discussed below, we are also considering various phase-in approaches for implementing the low sulfur diesel standard. A phase-in could help spread out the design, construction, and capital expenditure of refinery modifications necessary to comply with the proposed diesel fuel sulfur standard.

API also believes that those refiners facing higher than average costs may decide to leave the highway diesel fuel market. API also believes that many refiners may reduce their production of highway diesel fuel, by switching the feedstocks which are most difficult to desulfurize to other markets. However, while minimizing costs is one likely goal of refiners, maximizing profits is likely a higher goal. The belief that some refiners may reduce or eliminate production of highway diesel fuel would present an opportunity of higher profits for those refiners more willing to invest and stay in the market. Thus, we do not believe that refiners would give up the on-highway diesel fuel market easily. For example, the refining industry actually overbuilt desulfurization capacity for the current 500 ppm standard, as evidenced by the significant use in the off-highway market of diesel fuel produced to the current highway diesel sulfur standard of 500 ppm. Some of this overproduction may have been due to limitations in the distribution system to distribute both highway and off-highway grades of diesel fuel. Despite the overall market overproduction, a number of small refiners did decide to switch from the highway diesel fuel market to the off-highway diesel fuel market, presumably for economic reasons.

The domestic off-highway diesel fuel and heating oil markets are much smaller than the on-highway diesel fuel market. The domestic off-highway diesel fuel and heating oil markets are currently in balance, considering the significant amount of on-highway diesel fuel which is currently being sold into these markets. Given the refining cost of meeting the current 500 ppm sulfur cap, this over-production of fuel meeting the 500 ppm cap is likely attributable to limitations in the distribution system. Thus, assuming that the distribution system can be designed to more carefully distinguish between on-highway and other distillate fuels, a significant amount of current on-highway diesel fuel production could switch to these other markets with no loss of highway diesel fuel supply. In addition, although the off-highway diesel fuel market is growing, this growth will occur gradually over the next 6 years and not occur on April 1, 2006. The heating oil market is very seasonal (strong in the winter and weak in the summer), regional (strong in the Northeast) and not growing. Thus, overall, we do not see much opportunity for large domestic producers of highway

diesel fuel to be able to shift their production to these other domestic markets.

Exports of diesel fuel are also limited to some degree. Japan and Europe will have stringent sulfur caps in place by 2005 and have cetane requirements well beyond the cetane levels of current U.S. diesel fuel. Asia, while growing in demand for diesel fuel, has also been the focus of new grassroots refinery production and again has high cetane requirements. Thus, the primary areas for export would appear to be Africa and Latin America.

Refiners have also raised the possibility of shifting some of their more difficult to desulfurize diesel feedstocks such as LCO to other distillate markets or export. While this may be a possibility to some degree as discussed in section IV and the draft RIA, the opportunities to do so appear to be limited. The cetane level of the LCO feedstock does not allow it to be used as diesel fuel by itself. Only small additional amounts could be blended into off-highway diesel fuel without failing the cetane or other specifications for diesel fuel. Consequently, its only use without additional treating would be in home heating fuel where cetane is not a constraint. Even if some shifting of LCO feedstocks to off-highway diesel fuel or home heating fuel was possible, it is likely that refiners would in exchange shift a similar magnitude of other, more easily desulfurized feedstocks (i.e., straight-run distillate) currently comprising these other distillates into highway diesel fuel production. As a result, we would not expect any overall impact on highway diesel volume.

9. Conclusions

In order to meet the proposed 15 ppm sulfur cap, refiners are likely to further hydrotreat their highway diesel fuel in much the same way as it is being done today to meet the 500 ppm sulfur cap. Improvements to current hydrotreaters can be used to reduce diesel fuel sulfur beyond that being done to meet the 500 ppm cap. However, these improvements alone do not appear to be sufficient to provide compliance with the proposed 15 ppm cap. Based on past commercial experience, it is very possible to incorporate current distillate hydrotreaters into designs which provide compliance with the proposed 15 ppm cap. Thus, the equipment added to meet the 500 ppm standard in the early 1990's will continue to be very useful in meeting a more stringent standard.

The primary changes to refiners' current distillate hydrotreating systems would be:

- 1) the use of a second reactor to increase residence time, possibly incorporating counter-current flow characteristics, or the addition of a completely new second stage hydrotreater,
- 2) the use of more active catalysts, including those specially designed to desulfurize sterically hindered sulfur containing material,
- 3) greater hydrogen purity and less hydrogen sulfide in the recycle gas, and
- 4) possible use of higher pressure in the reactor.

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Existing commercial hydrotreaters are already producing distillate with average sulfur levels below 10 ppm, which should be more than sufficient to meet a 15 ppm cap. These hydrotreaters are processing distillate with typical breakdowns of SRGO, LCO and LCGO. Therefore, the proposed 15 ppm cap appears to be quite feasible given today's distillate processing technology. The only drawback of these commercial demonstrations is that they were designed to reduce aromatics content, or improve cetane, as well as reduce sulfur. Therefore, these units' hydrogen consumption and its associated cost are higher than that needed for simple sulfur removal. This combination of sulfur and aromatics reduction has been encouraged by fuel tax incentives in Europe. The incentive to reduce sulfur by itself to such low levels has not existed, so refiners have generally had no incentive to produce such a product commercially.

Advances continue to be made in catalyst technology, with greater amounts of sulfur being able to be removed at the same reactor size, temperature and pressure. Therefore, it is reasonable to expect that distillate hydrotreaters put into service in the 2006 timeframe will utilize even more active catalysts than those available today.

Other methods of reducing diesel fuel sulfur, such as FCC feed hydrotreating, removing the heavy end of LCO, etc. help to reduce diesel fuel sulfur levels, but will generally not be sufficient to provide compliance with a 15 ppm cap. However, we expect that a number of refiners will utilize these techniques to reduce the severity of their distillate hydrotreaters and reduce hydrogen consumption (particularly by avoiding aromatic saturation). Some of these techniques would tend to increase the supply of highway diesel fuel (e.g., FCC feed hydrotreating), while others would tend to decrease it (e.g., removing the heavy end of LCO).

Biodesulfurization technology holds promise to reduce distillate sulfur without the high temperatures and pressures involved in hydrotreating. Efforts are underway to demonstrate that this technology can achieve 50 ppm sulfur or less in the next few years. However, it is not clear whether this technology would be sufficient to meet a 15 ppm cap.

B. Interaction with Other Programs

In addition to the program proposed today, there are a number of other environmental programs that may concurrently have an impact on the refining industry. The most significant of these programs is the recently promulgated gasoline sulfur standards as part of the Tier 2 rulemaking. We have examined the impacts on engineering, construction, and capital expenditures of gasoline sulfur control in conjunction with the diesel sulfur control program proposed today.

A particular concern has been raised to the Agency regarding the capability of the engineering and construction (E&C) industries to be able to design and build diesel fuel hydrotreaters while at the same time doing the same for gasoline, as well as accomplishing their other objectives. We believe that the E&C industry is capable of supplying the oil refining industry with the equipment necessary to comply with the proposed diesel fuel sulfur cap on time. We

believe that this is facilitated by the extended phase-in we allowed regarding compliance with the Tier 2 gasoline sulfur standards. Overall, we project that nearly two-thirds of all gasoline-producing refineries outside of California will have completed the design and construction of their desulfurization equipment prior to the need to do so for diesel.³² Thus, most of the construction related to gasoline desulfurization will be completed prior to implementation of the diesel fuel sulfur cap. Also, low sulfur gasoline and diesel fuel standards scheduled for Europe become effective in 2005. Low sulfur gasoline standards take effect in Canada in 2002 and 2005. These standards precedes the proposed highway diesel fuel sulfur cap sufficiently to enable the availability of European equipment fabrication capacity to be available to meet the needs of the proposed sulfur cap in the U.S. Thus, we do not foresee any shortage in either E&C industry personnel or equipment fabrication capacity. We request comment on these findings.

Similar concerns have been raised with respect to the refining industry's ability to raise the capital necessary to make the refinery modifications necessary for diesel fuel, while at the same time doing so for gasoline. We have designed these programs in a manner which will serve to maximize refiner flexibility and minimize costs. In the gasoline sulfur control program refiners have the flexibility to take actions to reduce sulfur in their gasoline starting as early as 2001 and extending as long as 2006. Small refiners have even more flexibility, including the ability to defer full compliance until 2008 and in extreme cases as late as 2010. Under our proposal, diesel sulfur control investments would not occur until gasoline sulfur control investments begin to taper off. In the preamble to this proposed rule, we request comment on several approaches that would allow refiners to phase in implementation of the proposed highway diesel sulfur standard.

The following table presents the projected stream of capital investments which are expected to result from the Tier 2 gasoline sulfur standards, as well as the proposed diesel fuel sulfur cap. As can be seen, roughly two-thirds of the capital investment for diesel fuel desulfurization would occur in 2005, the year before the proposed cap would become effective. Peak capital investment of \$2.75 billion would occur in 2005. This level is equivalent to that spent by the refining industry in the early 1990's. With a phase-in of the proposed diesel fuel sulfur cap, this capital investment would be spread out over subsequent years and the peak investment in any single year would be lower. Almost two-thirds of the refinery capital expenditures for gasoline sulfur control will have occurred prior to 2004 and 2005 when we anticipate the capital expenditures for diesel fuel sulfur control to occur.

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Table IV.B-1: Capital Expenditures for Tier 2 Gasoline and Proposed Diesel Fuel Desulfurization			
<i>Calendar Year</i>	<i>Gasoline</i>	<i>Diesel Fuel</i>	<i>Total</i>
2002	1.31*		1.31*
2003	1.45*		1.45*
2004	0.72	1.9	2.62
2005	0.75	2.0	2.75
2006	0.24	0.2	0.44
2007	0.07		0.07

* Includes pre-2004 capital expenditures used to generate early sulfur reduction credits

In addition to gasoline sulfur control there are other environmental programs that could also concurrently have an impact on the refining industry. The phase-down of MTBE from gasoline is currently under consideration. While the nature of the action on MTBE has not yet been determined, if EPA acts to reduce or eliminate MTBE usage, we will consider cost impacts on refiners and provide sufficient lead time (e.g., 3 to 5 years) to comply with such requirements.

Collectively, we anticipate that these programs will provide enormous air quality benefits to the American public that are expected to far outweigh the costs. These emission reductions will contribute greatly to reduced exposure to harmful ozone, air toxics, and particulate matter pollution. They will also reduce acid deposition, eutrophication and nitrification of, and POM deposition to, our Nation's waterways and the haze that interferes with visibility across the country, especially in our national parks. Compared to other programs that would need to be implemented to achieve emission reductions, the cost effectiveness of these programs is very attractive.

C. The Need for Lubricity Additives³³

1. What Impacts Will the Proposed Sulfur Change Have on Lubricity?

Diesel fuel lubricity is the characteristic of diesel fuel to provide sufficient lubrication to protect each of the many contact types within fuel pumps and injection systems for reliable performance. Unit injector systems and in-line pumps, commonly used in heavy-duty engines, are actuated by cams lubricated with crankcase oil, and have minimal sensitivity to fuel lubricity. However, rotary and distributor type pumps, commonly used in light and medium duty diesel engines, are completely fuel lubricated, resulting in high sensitivity to fuel lubricity. Low fuel lubricity has been associated with low-viscosity fuels, such as No.1 diesel fuel or kerosenes, which are typically used in cold climates. As a result, many rotary fuel injection systems intended for use

in cold climates contain components manufactured using improved metallurgy specifically to tolerate the use of poorer lubricity fuels.

Experience has shown that it is very rare for a naturally high-sulfur fuel to have poor lubricity, although most studies show relatively poor overall correlation between sulfur content and lubricity. One study indicated a relationship between diesel fuel lubricity and the content and composition of sulfur compounds. However, the artificial addition of sulfur compounds seems to have no effect or even a slight detrimental effect at high concentrations. Another study showed that fully-saturated hetrocyclic sulfur compounds are the most active naturally occurring fuel lubricity agents. High molecular weight components, back-end volatility, naphthalenes, polyaromatics, nitrogen compounds, polar compounds (excluding sulfur and nitrogen compounds) and oxygen compounds have been identified as potential lubricity agents. There is some indicated correlation between total aromatics content and lubricity, as measured by laboratory tests. The addition of aliphatic kerosene fractions to diesel fuel, which have inherently lower lubricity, can also decrease the lubricity of the resulting blend.

Unfortunately, few consistent trends are visible in the literature, and some researchers have shown that properties such as sulfur, aromatics, acidity and olefin content cannot be used alone to predict fuel lubricity. At present, the most that can be said definitively regarding the impact of fuel composition on lubricity is that a single fuel with low viscosity, low sulfur, aromatics and acid content generally will tend to have poorer lubricity than those with higher levels. Considerable research remains to be performed regarding the fuel components most responsible for lubricity. Consequently, successful application of either a chemical test or predictive model depends on a better understanding of the fuel and additive components responsible for lubricity.

Hydrotreating, in addition to reducing sulfur content, can lead to a reduction in the concentration of various compounds which may contribute to fuel lubricity such as aromatics and high molecular weight hydrocarbons. As early as 1976, it was suggested that lowering the level of aromatics, separation of sulfur compounds and polar substances, as well as separation of surface-active substances during the hydrotreating refining process, can result in a reduction of the lubrication qualities of the fuel. One report³⁴ suggested that reduction in lubricity is caused by the removal of the sulfur that itself acts as a lubricant, and the removal of some compounds such as furans, pyroles and thiophenes in the refining process. In one 1992-93 study, extremely low aromatics content produced by hydrotreating caused catastrophic failure of rotary fuel injection pumps. Unfortunately, few consistent trends are visible in the literature, and some researchers have shown that properties such as sulfur, aromatics, acidity and olefin content cannot be used alone to predict fuel lubricity.

Similarly, the aviation community has investigated the lubricity of jet fuel. The most satisfactory explanation for wear on failed aviation components has been a simple corrosive process, involving the repeated formation and removal of metal oxides during sliding. To a lesser extent, wear has been explained by severe adhesive wear and scuffing as the component dimensions were reduced beyond tolerable limits or if contact loads were unusually high. Severe refinery treatment

removes the naturally occurring corrosion inhibitors from the fuel, allowing formation of a thick oxide layer. The removal of chemically active species to upgrade thermal stability was found to be associated with poorer fuel lubricity. A number of studies by the middle to late 1960s indicated that poor performance of high-purity jet fuel appeared to be related to the availability of naturally occurring compounds, rather than gross physical or chemical properties. Other studies indicated that fully saturated hetrocyclic compounds and polynuclear aromatic hydrocarbons have a beneficial effect on lubricating characteristics. As little as two percent aromatics greatly increased the load-carrying capacity of paraffins. Mixtures of heavy aromatics and paraffins were much more effective than either compound used alone. One study also found complex esters and, to a lesser extent, high molecular weight polymers to be effective as anti-wear agents in turbine and diesel fuel. Another study found that the lubricity of severely refined fuels could be improved by the addition of trace concentrations of surface-active additives, such as corrosion inhibitors.

Some studies have indicated that the presence of water may have a significant effect on lubricity values, although apparently only humidity values were monitored and controlled for those studies. The U.S. Navy conducted a study to determine the effects of humidity and water on distillate lubricity using the BOCLE, SLBOCLE, and HFRR tests³⁵ (these tests are described in the next subsection). The results of this study indicated that the test fuels were not noticeably affected by any of the water introduction methods using any of the three test procedures.

Notwithstanding all these uncertainties, hydrotreating has been known to reduce the lubricity of the treated fuel, depending on the severity of the treatment and characteristics of the crude. If as anticipated, refiners increase the severity of their hydrotreating to comply with the proposed sulfur standard, the lubricity of some batches of fuel may be reduced compared to today's levels. To compensate for the potential impact on fuel lubricity, we have accounted for an increased use of lubricity additives in highway diesel fuel in our cost calculations.

2. How Can One Determine Whether the Lubricity of a Fuel Is Adequate?

Many researchers have demonstrated that the correlation between the different wear mechanisms in fuel pumps is dependent on the fuel composition. This is particularly important for dissimilar wear mechanisms, such as oxidative corrosion and adhesive scuffing. The most successful wear tests appear to be those that reproduce the predominant (i.e., the most damaging) wear mechanisms. However, there is considerable disagreement as to the relevant importance of each mechanism and also to the appropriate laboratory-scale test procedure to measure lubricity. A number of studies have observed poor correlation between pump wear and the most widely used laboratory test procedures, and no single wear test provides a complete description of lubricity. In addition, these tests appear less effective when evaluating fuels that contain additives, compared to the base fuels. Several studies have reported that the laboratory tests predict negligible benefits from lubricity additives, but fuel trials indicate that lubricity additives do provide acceptable lubricity.

Many laboratory fuel tests which are designed to operate under boundary lubricating conditions are strongly correlated to viscosity. For many crude sources, a disproportionate fraction of sulfur-containing compounds are contained in the higher molecular weight fuel components, indicating an intrinsic relationship between chemical and physical fuel characteristics. One researcher successfully developed a simple empirical relationship that predicted fuel lubricity as measured using the SLBOCLE test (described below) using viscosity and di-aromatic content. Unfortunately, such a model does not account for the effects of trace constituents or lubricity additives. In 1993, the U.S. Army systematically defined the principal wear mechanisms as oxidative corrosion, chemical corrosion, adhesion, and scuffing (severe adhesion), with oxidative and scuffing predominating. In that study, the degree of pump wear seemed to be highly sensitive to the availability of dissolved moisture, indicating the presence of an oxidative mechanism.

The BOCLE (Ball-on-Cylinder Lubricity Evaluator) apparatus uses a ball-on-rotating cylinder contact geometry. The primary wear mechanism produced by this test was found to be oxidative corrosion and possibly the chemical corrosion mechanism found in high-sulfur fuels. The U.S. Army sponsored development of a modified BOCLE - the SLBOCLE (Scuffing Load Ball-on-Cylinder Lubricity Evaluator) - in 1994, to measure fuel load-carrying capacity. It measures the applied load required to produce a transition from mild boundary lubricated wear to adhesive scuffing. To minimize the effects of oxidative corrosion and abrasive wear, the SLBOCLE uses a polished test ring in place of a ground specimen. A Society of Automobile Engineers (SAE) paper concluded that the SLBOCLE test is a good tool to evaluate the lubricity of base fuels, which contain no lubricity additive.³⁶ However, this method can distinguish additives only if large amounts are used, well above the concentrations required to protect the equipment.

The HFRR (High Frequency Reciprocating Rig) was developed in Europe in 1986. The apparatus consists of a AISI E52100 steel ball, which reciprocates against a polished plate of the same material. The mean wear scar diameter formed on the ball is used as a measure of lubricity. This test produces a very wide range of wear mechanisms, depending on the fuel being evaluated. However, SAE paper 961948 concludes that the correlation between fuel injection pump rig and HFRR results have not been satisfactory. Many fuels which were regarded good according to a pump demerit wear rating were regarded poor according to the HFRR.

In 1991, the Society of Automotive Engineers (SAE) formed a committee to evaluate the effects of reduced fuel lubricity and to identify an effective laboratory wear test procedure. In Europe, the Coordinating European Council (CEC) was established for the same purpose. In 1992, both groups cooperated under the auspices of an International Standards Organization (ISO) working group. Following a systematic evaluation of the available test procedures, the group performed a round robin test program to compare the HFRR, two variants of the BOCLE, and the Falex BOTS (Ball-on-Three Seats) test. This work was backed up by full-scale pump tests performed by the original equipment manufacturers using a matrix of 12 fuels. A HFRR result of 450 microns was recommended by the ISO working group, and 460 microns by the CEC, as the maximum result for acceptable lubricity. No official minimum SLBOCLE result has been defined, but the ISO working group data and most studies indicate that an SLBOCLE result of approximately

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3,000 grams delineates the transition between acceptable and poor lubricity. The ISO is involved in a Phase 2 study to include additized fuels, which were largely ignored in the original study. The objective is to evaluate the correlation between injection equipment rig tests and the HFRR test for additized fuels. No conclusion was reached at the time of publication of SAE 1999-01-1479 in May 1999.

The American Society for Testing and Materials (ASTM) lubricity task force evaluated the information that had been generated by previous working groups, including ISO, and recommended that the SLBOCLE and HFRR tests be adopted as ASTM test methods. However, the ASTM group chose not to adopt ISO's 450 micron specification and has not included a minimum lubricity requirement in ASTM D-975 specifications for diesel fuel quality. In addition to the additive problem, the two ASTM test methods (SLBOCLE and HFRR) suffer from poor precision and do not correlate well with each other. The ASTM group decided it needed to conduct more work to improve the precision of the test methods, resolve the discrepancy between the test results and the actual field experience, and modify the test methods to apply to additized fuels. A fuel specification will be considered after the test issues are resolved. The ASTM group is evaluating a recent BOTD (Ball on Three Disks) test, along with a modification to the existing HFRR method.

Chevron conducted a limited number of tests with additized fuels. In all cases, the HFRR test was indicated to be the least responsive to additive concentrations. This method does not recognize the existence of any additive up to levels above 100 ppm, and full benefit is indicated at levels between 200 and 500 ppm. The SLBOCLE test recognizes an additive effect between 40 and 50 ppm, and detects the full potential of the additive between 50 and 200 ppm. The BOTD test recognizes an additive effect at a level as low as 10 ppm, and detects the full additive potential at around 20 to 40 ppm. Early reports by a recent effort at Southwest Research Institute indicate that the HFRR test discrimination of additized fuels could be improved by changes to the frequency and stroke.

3. What Experience Has There Been with Low-sulfur Fuels?

What has been the experience with aviation turbine engines?

Aviation turbine kerosene (Jet A, Jet A-1) is the principle fuel used by commercial airlines. A wide cut fuel spanning the gasoline and kerosene boiling range (JP-4, Jet B) has historically been used by many national air forces. A higher flash point fuel (JP-5) has been used for naval aircraft. Compared to both low and high sulfur diesel fuels, aviation kerosene fuels tend to be poor lubricants.

In 1969, the British Ministry of Defense formed a Fuel Lubricity Panel to specify a lubricity parameter for aviation turbine fuel. The panel was unable to specify a lubricity test that would accurately reflect the lubricity requirements of an aviation turbine fuel, but it did suggest that a ball-on-cylinder machine showed promise. In the mid-1970's, the U.S. Navy began to experience

durability problems on equipment operated with fuels from refineries outside the continental U.S. Failures were reported for afterburner hydrolic fuel pumps and also hang-up of fuel controls. The U.S. Navy in cooperation with the Coordinating Research Council (CRC) Aviation Fuel Lubricity Group began a detailed evaluation of the BOCLE apparatus. That study recommended that the BOCLE apparatus continue to be used to evaluate lubricity of fuels from the aircraft fleet, as well as the use of corrosion inhibitors in military aviation fuels. The study also recommended that new aircraft and fuel system components be developed to operate satisfactorily on low-lubricity fuel.

Since 1975, the approach of the commercial aviation community has been to maximize equipment durability through improved materials and design, rather than through control or measurement of fuel lubricating characteristics. However, the approach of the military has been to add corrosion inhibitors to the fuel. Currently, many military aircraft use JP-8 fuel, which is generally equivalent to Jet A-1 treated with several additives, including a corrosion inhibitor to improve lubricity. As a result of these efforts, the aviation community has reported only isolated problems related to lubricity. Research is in progress relating to future advanced turbine engines in which the incoming fuel will be exposed to temperatures reaching 163 °C and as high as 315 °C.

What has been the experience with compression ignition engines?

Unit injector systems and in-line pumps are actuated by cams lubricated with crankcase oil, and have minimal sensitivity to fuel lubricity. Rotary and distributor type pumps, commonly used in light and medium duty diesel engines, are completely fuel lubricated, resulting in high sensitivity to the effects of lubricity. As a result, the rotary fuel injection system has been the primary focus of lubricity research. As noted as far back as 1970, blending diesel fuel with a small concentration of good lubricity fuel has a disproportionately large effect on the wear characteristics of a blend. Blending or mixing different fuels minimizes the effect of isolated poor lubricity products. It has been observed that most equipment failures occur in fleets that are supplied from a single fuel source.

What has been the experience of the U.S. Military?

Military vehicles are particularly susceptible to the effects of fuel lubricity, as a given post or camp or station will use fuel from a single supplier for a minimum contract period of 12 months. As a result, little potential exists for blending of fuels from different sources. In the 1970s, the Army approved JP-5 as an alternative to DF-2 (VV-F-800) diesel fuel. In the 1980s, the Department of Defense (DOD) adopted a single fuel for the battlefield and converted its tactical fleet of compression ignition powered vehicles from DF-2 to aviation turbine fuel (MIL-T-83133). In March 1988, DOD specified JP-8 as the primary fuel support for overseas ground forces, but considered it and Jet A-1 equivalent fuels. Jet A-1 does not contain the corrosion inhibitor additives of the JP-8 fuels. During Operation Desert Storm, the military experienced rotary diesel fuel pump failures on its vehicles when operated on Jet A-1. While examinations of the failed fuel injection components indicated the majority of failures were attributed to causes other than lubricity, the Jet A-1 did appear to produce increased wear in some areas of the pumps. Tests performed with

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rotary injection pumps on a motorized test stand indicated very severe wear was produced with Jet A-1 in as little as eight hours. Wear rate was significantly reduced by the corrosion inhibitors specified for use in JP-8. Subsequently, the U.S. military no longer considered those fuels to be equivalent. The military noticed vehicle fuel system component wear when fuels with a SLBOCLE value of less than 2,000 grams were used consistently. The wear became significant for fuels with a SLBOCLE value of less than 1,600 grams.

What has been the experience of the U.S. commercial sector?

No widespread failures associated with poor fuel lubricity have been reported in the United States, although on average, its diesel fuel has borderline lubricity, based on the HFRR test. Fuel sulfur levels have been restricted to 500 ppm nationwide since 1993, except for Alaska and certain territories. In commercial vehicles, the beneficial effect of blending different fuels is likely to occur.

When lubricity has been a problem, failures that have been reported involved the use of No. 1 type diesel fuels with viscosities below 2.0 cSt at 40°C. Very low ambient temperatures, aside from the obvious effect on viscosity, greatly reduces the solubility of moisture in the fuel. Dissolved moisture is necessary for the oxidative corrosion wear mechanism to occur. Many rotary fuel injection systems intended for use in cold climates contain components manufactured using improved metallurgy specifically for this reason. Many municipal bus fleets in the continental United States operate year round using low viscosity diesel fuel, such as DF-1, to minimize exhaust emissions. In practice, many operators procure aviation kerosene fuels, particularly in more temperate southern areas where low viscosity diesel fuel is not readily available. Anecdotal reports of injection system failures with these fuels are relatively common, with replacements occurring as early as 15,000 miles in some instances.

What has been California's experience?

Low sulfur (500 ppm) diesel fuels have been marketed in Southern California since 1988. Beginning October 1993, diesel fuels marketed in all of California had to meet the new Federal sulfur standard of 500 ppm and a new state requirement of 10 percent aromatics by volume, or equivalent emissions. In 1989, a few researchers, including fuel suppliers and engine and equipment manufacturers, recognized that the regulations to reduce the aromatics content in 1993 would have the potential to affect equipment if the fuel lubricity was reduced substantially. Of particular concern was the protection of rotary distributor pumps used in passenger cars, light vans and trucks, and much of California's agricultural equipment.³⁷

A Governor's Task Force on diesel fuel was created to investigate concerns regarding lubricity and other properties of the reformulated fuel. As a result, for three years from October 1993, through 1996, staff of the California Air Resources Board monitored fuel injection system problems (and also price increases and reports of supply shortages), and recommended that fuel suppliers monitor the lubricity of their fuel using the U.S. Army's SLBOCLE test or other appropriate test and add lubricity enhancing additives to diesel fuel with a SLBOCLE test result

below 3,000 grams. The 3,000 gram level was a compromise between the 2,220 gram level suggested by the American Petroleum Institute (API) and the 3,330 gram level requested by Engine Manufacturers Association (EMA). Diesel fuels marketed in California are blended from various refinery products and contain lubricity enhancers and other additives. As previously discussed, the SLBOCLE test lacks precision in evaluating additized fuels and underestimates the benefit of lubricity additives. Thus, the test results were considered an indication of the lubricity of the base fuel, and a worse case of actual fuel lubricity. Cetane-enhanced alternative formulation fuels, with aromatic content near 20 percent, were not hydrogenated as severely, and thus were not as dependent on additives for acceptable lubricity.³⁸

During the three year monitoring period of 1993-1996, no lubricity-related fuel pump damage was documented for diesel vehicles using California fuel. Also, analysis of the data showed no strong correlation of lubricity with either sulfur or aromatic content. At first, only 30 percent of the fuels evaluated met or exceeded the 3,000 gram level. The average SLBOCLE results for California fuels increased from 2700 grams in 1993 to 3,300 grams in 1996. This improvement may be attributed to use of lubricity additives, combined with increasing production of alternative formulations and blended products, which perform better on the SLBOCLE test than do low aromatic products with lubricity additives.³⁹

What has been Canada's experience?

Overall, Canadian fuels tend to have low density, low viscosity, and lighter distillation characteristics than those used in the United States, and are among the worst lubricity fuels in the world. Diesel fuel No. 1, as used for much of the year in Canada, is broadly similar to the kerosene fuels that caused durability problems in military vehicles, municipal buses, and aviation equipment. Even prior to the introduction of low-sulfur diesel fuel, Canada had reported problems with reduced equipment life. These failures were typically associated with winter grade diesel fuels, particularly when they were used in warmer conditions. Low-sulfur fuels have been available in Canada since the 1980s, and a maximum sulfur content of 500 ppm was mandated in 1994. Fleet testing repeatedly demonstrated catastrophic pump failure in less than 500 miles of operation on Canadian fuel. In 1997, Canada modified its low-sulfur diesel fuel specification to address the lubricity of winter fuels - those having a viscosity below 1.9 cSt at 40°C or less and a cloud point of -30°C or lower. A fuel supplier can "qualify" its fuel using one of several options, ranging from a field test to pump rig tests to the HFRR or BOCLE laboratory scale test. A fuel supplier must use lubricity additives if the fuel fails the selected test.

What has been Sweden's experience?

Beginning in 1991, Sweden required very low concentrations of sulfur and aromatics in its diesel fuels: maximum of 10 ppm sulfur and 5 percent by volume aromatics for Class I fuel, and maximum of 50 ppm sulfur and 20 percent by volume aromatics for Class II fuel. Field trials and research conducted by the fuel producers and equipment manufacturers indicated that these fuels, without additives, would produce unacceptable wear of light-duty injection systems. Failure of test

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rotary fuel pumps occurred between 5,000 and 19,000 miles for Class I fuel, and between 8,000 and 48,000 miles Class II fuel. Heavy-duty inline pumps were less susceptible to low lubricity fuel. This experience drew more attention and interest to the possibility of a widespread fuel lubricity problem in the rest of Europe and in North America at the time they were introducing their lower sulfur and lower aromatic fuels. Since that time the use of lubricity additives in Sweden's fuel has resulted in acceptable equipment durability.

What has been Asia's Experience?

In the Far East, a number of countries have already or will soon implement a 500 ppm sulfur maximum: Korea in 1996, Japan in 1997, Hong Kong in 1997, Taiwan in 1999, Thailand in 1999, Philippines in 2000, Australia in 2003, and New Zealand in 2005. Research is being performed to determine the effects of Asian low-sulfur fuel on injection system durability, and except for one study in Thailand, results have not yet been published.

In Thailand, a field study was conducted to investigate the effects of low-sulfur diesel fuel (500 ppm) without lubricity additives on rotary injector pumps operating in actual driving conditions in Thailand.⁴⁰ The study involved three vehicles each for two fuels for 30,000 km. The first fuel was imported and made up of a blend of U.S. West Coast, Malaysian and locally refined fuel having a HFRR test value of 358 μm . The second fuel was the first batch of locally produced low-sulfur fuel with a HFRR test value of 467 μm . Evidence of wear at the end of the study were within the normal acceptable range of wear at 30,000 km for all six pumps, although the pumps operated on the locally refined fuel showed nearly twice as much wear, on average, as the pumps operated on the imported blend.

4. What Can Be Done About Poor Lubricity Fuels?

Blending poor lubricity diesel fuel with a small concentration of good lubricity fuel has a disproportionately large effect on the wear characteristics of the blend. Thus, blending or mixing different batches of diesel fuel, such as that which occurs in the commercial market in the United States, minimizes the effect of isolated poor lubricity fuels.

Also, blending small amounts of lubricity enhancing additives has increased the lubricity of poor-lubricity fuels to acceptable levels. Laboratory testing, field experience and controlled pump and vehicle testing indicate that additives can be effective in reducing pump wear. The lubricity additives currently used in diesel fuels range from the corrosion inhibitors used in aviation turbine fuel to fully synthetic non-acidic products. The additives' impact on pump wear appears to be strongly influenced by fuel composition and distillation characteristics, with larger improvements observed for poorer lubricity fuels. According to contacts in the industry and an SAE report, oil companies are likely blending additives to diesel fuel on a batch-to-batch basis when poor lubricity fuel is expected.

Sweden, Canada, and the U.S. military offer examples of experiences using additives to improve the lubricity of diesel fuel. Since 1991, the use of lubricity additives in Sweden's fuel has resulted in acceptable equipment durability. Since 1997, Canada has required that diesel fuel not meeting a minimum lubricity be treated with lubricity additives. The U.S. military has found that traditional corrosion inhibitor additives that it uses, such as di-linoleic acid, have been highly effective in reducing fuel system component wear. Consequently, the U.S. Army now blends 250 mg/L of MIL-I-25017E corrosion inhibitor additive to all fuels that show a SLBOCLE result below 2,000 grams, and regularly for Jet A-1, JP-5 and JP-8 fuels.

According to the literature, lubricity additives have not been found to significantly affect exhaust emissions. However adding too much can produce unwanted side effects, such as deposits in in-line injection pumps, fuel filter plugging, injector tip deposits, plunger sticking, and water haze problems. For these reasons, the selection and treat rate of an additive are important. An SAE report indicated it is likely that the more recently developed non-acid based additives provide improved performance with reduced problems from lubricant interaction. For example, in early 1996, field problems occurred in Western Europe with vehicles fitted with in-line diesel injection pumps. Fuel filters were being blocked with black sticky gel caused by the use of lubricity additives based on a specific type of divalent acid.⁴¹

The literature indicates that treat rates typically vary from 20 to 200 mg/L. Higher concentrations are occasionally used, although in general, benefits appear to decrease at concentrations above 500 mg/L. Oxidative corrosion and associated sensitivity to moisture are eliminated by trace quantities of corrosion inhibitor additives. However, these additives have little or no effect on adhesion and scuffing wear mechanisms. While corrosion and rust inhibitor additives are commonly blended to distillate fuels at 10-15 ppm by the petroleum producers to protect transport pipelines, this low concentration provides little protection to consumers because of leaching during transportation and handling.

Also, it is possible for equipment producers to design new injection system equipment to tolerate lower lubricity fuels. Revised manufacturing practices to include improved materials successfully allowed commercial aircraft to operate continuously with very poor lubricity kerosene-based fuels. Studies sponsored by the U.S. Army also confirmed the possibility of reducing or eliminating the effects of poor lubricity through the use of improved metallurgy. This approach could be applied to fuel systems for commercial compression ignition engines. Conversion kits are already available to allow many pump systems to operate on low-lubricity/low viscosity fuels and are commonly used on engines in Arctic regions. For the purposes of this rule, we will assume that such conversions will not be commonplace in the commercial vehicle and vehicle engine market.

5. What is EPA Proposing?

Under our proposed approach we would "encourage", but not require, fuel producers and distributors to monitor and provide fuel with adequate lubricity to protect diesel engine fuel systems.

This proposal is similar to California's approach when it implemented the low-aromatic requirements in the early 1990's, and it is reasonably expected to be successful based on California's experience. In addition, this approach recognizes the uncertainties of testing and measuring fuel for lubricity, and allows flexibility as research produces better information and improved test methods. On the down side, voluntary measures do not guarantee results, but we believe the risk in this case is small. Refiners and distributors have an incentive to supply fuel products that will not damage consumer equipment. Even if occasional batches of poor lubricity fuel are distributed, they would likely be "treated" with residual quantities of good lubricity fuel in storage tanks, tanker trucks, retail tanks, and vehicle fuel tanks. Further, we expect that the American Society for Testing and Materials intends to address lubricity in its ASTM D-975 specifications for diesel fuel quality after its concerns about test issues have been resolved.

6. Are There Concerns Regarding the Impact of Diesel Desulfurization on Other Fuel Properties?

With the introduction of low-sulfur diesel fuel in the United States in 1993, some fuel pumps with a Nitrile material for O-ring seals began to leak. Fuel pumps using a Viton material for the seals did not experience leakage. The leakage from the Nitrile seals was determined to be due to low aromatic levels in some low-sulfur fuel, not the low sulfur levels. In the process of lowering the sulfur content of some fuel, some of the aromatics had been removed. Normally, the aromatics in the fuel penetrate the Nitrile material and cause it to swell, thereby providing a seal with the throttle shaft. When low-aromatic fuel is used after conventional fuel has been used, the aromatics already in the swelled O-ring will leach out into the low-aromatics fuel. Subsequently, the Nitrile O-ring will shrink and pull away, thus causing leaks, or the stress on the O-ring during the leaching process causes it to crack and leak. Not all low-sulfur fuels will cause this problem, because of the amount and type of aromatics will vary. One engine manufacturer recommended replacement of the old O-ring seals in leaking fuel pumps with a new part of the same material, reasoning that the new part is not worn or has not taken a compression set. One fuel producer recommended switching all fuel injection pump applications to Viton seal material. While the market has apparently resolved this issue, it may warrant additional investigation.

D. Feasibility of Maintaining Low-Sulfur Fuel in the Distribution System

The sulfur content of diesel fuel can be influenced after it leaves the refinery either by the intentional use of additives or by contamination in the distribution system. We have proposed that all diesel fuel additives meet the same 15 ppm cap on sulfur content that is proposed for diesel fuel. This would ensure that the use of additives in diesel fuel would not jeopardize compliance with the proposed cap on diesel sulfur content. We anticipate that capping the sulfur content of diesel additives would result in minimal additional burden (see Section IV.D.1.). Based on our evaluation of the feasibility and costs of reducing sulfur contamination in the diesel distribution system, balanced against the increased cost to refiners of producing diesel fuel at progressively lower sulfur levels, we believe that such contamination (in aggregate) can be reasonably limited to increase the sulfur content of diesel fuel by no more than three ppm. In large part, our evaluation indicates that this can be achieved by consistently and carefully observing current industry practices to limit contamination. We anticipate pipeline and terminal operators would need to take some additional steps to adequately limit contamination. These additional measures are expected to result in a modest additional burden to industry (see Section IV.D.2.) The costs of maintaining low-sulfur fuel in the distribution system are estimated in Section V.C.3.

1. Potential Fuel Additive Impacts on Diesel Fuel Sulfur Content

A variety of additives are added to highway diesel fuel for different purposes at different points in the distribution system. Some of these additives, as they are currently formulated, could have a significant impact on the sulfur content of highway diesel fuel if the proposed 15 ppm cap on diesel fuel sulfur content is adopted. Diesel fuel additives fall into two classes, based on the fraction of the finished diesel fuel they represent when they are used. Bulk additives, such as kerosene and oxygenates, are added in relatively large quantities in the volume-percent range, while “chemical” or “performance” additives such as biocides, corrosion inhibitors, cold-operability improvers, and detergents are added in concentrations expressed in parts per million. Concerns regarding the application of the proposed cap on sulfur content to these two classes of diesel additives are discussed in the following sections.

a. Bulk Additives

We identified kerosene as the only bulk diesel additive whose addition to diesel fuel as it is currently produced would cause concern regarding the impact on diesel fuel sulfur levels under the proposed standard. During the winter months in cold climates, many refiners blend a portion of the kerosene they produce back into their diesel fuel to “trim” cold-operability performance.^c In some

^c Cold-operability “chemical/performance” additives are sometimes used to reduce the amount of kerosene that is required.

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refineries this “trim” kerosene is blended into diesel fuel in the range of 20-40 volume percent. It is most appropriate to consider kerosene that is blended back into diesel fuel at the refinery level as a diesel blendstock rather than a bulk additive. Consequently, issues related to the desulfurization of kerosene-based diesel blendstocks are considered within the context of the preceding discussion on the feasibility of removing sulfur from diesel fuel (section IV.A.). The cost of desulfurizing such blendstocks was incorporated in the refinery model used to estimate the cost of desulfurizing diesel fuel (Chapter V). This section focuses on concerns related to the use of kerosene as a bulk additive to diesel fuel after the finished diesel fuel leaves the refinery gate.

Although refiners seek to match the cold-operability performance of their diesel fuel to seasonal requirements by using kerosene-based blendstocks as necessary, a competing incentive exists to limit the amount of kerosene that is blended back into diesel fuel since it is typically a higher-priced product than diesel fuel. In cases where temperatures are colder than the refiner anticipates, it sometimes becomes necessary for downstream parties to blend additional kerosene as a bulk additive into diesel fuel in order to ensure cold-operability performance. When the downstream addition of kerosene as a bulk additive is necessary, it is typically used at a concentration of approximately five volume percent. However, in cases where actual temperatures at the time the diesel fuel is used are far lower than those predicted by the refiner at the time the diesel fuel was produced, the volume of kerosene needed as a bulk additive could potentially approach the maximum rate at which trim kerosene is added at the refinery (40 percent).

Kerosene is currently segregated into different pools based on its sulfur content and other properties. Currently, the pool from which kerosene is drawn for blending with diesel fuel has a low enough sulfur content (~400 ppm) in relation to the highway diesel fuel sulfur standard (presently a 500 ppm cap) that its addition to diesel fuel does not cause the sulfur standard to be exceeded.^d However, this would not continue to be true if the proposed sulfur standard is adopted. Hence, our proposal requires kerosene blended with highway diesel fuel meet the same 15 ppm cap on sulfur content that is proposed for diesel fuel. Consequently, the addition of kerosene to highway diesel fuel would not be an issue for the distribution system if the proposed diesel sulfur standard is adopted.

We anticipate that refiners would desulfurize the entire pool from which kerosene is drawn for wintertime blending with diesel fuel. Kerosene is drawn from a narrow distillation band of the petroleum fraction from which diesel fuel can be manufactured. We anticipate refiners will desulfurize kerosene in much the same manner as diesel fuel (as discussed earlier). We believe that it will be most cost effective for refiners to operate in this fashion compared with the relatively high cost associated with maintaining an additional grade of low-sulfur kerosene specifically for diesel blending purposes (at the refinery level for “trimming” and downstream as a bulk additive). The potential impact of this approach on the use of kerosene and cold-operability additives to maintain wintertime performance is discussed in Chapter V.D.

^d Kerosene from this pool also has other uses such as for home heating.

A variety of oxygenates are also used (or contemplated for use) in diesel fuel as bulk additives in concentrations of as much as 20 volume percent. However, such oxygenates are essentially sulfur free. Therefore, diesel oxygenates should have no difficulty in meeting the proposed sulfur standard and their use as currently manufactured would not adversely impact the sulfur content of diesel fuel.

b. Performance Additives

The concentration at which diesel performance additives are used varies considerably depending on their intended function, ranging from as little as a few ppm for anti-static additives to as much as 1,000-2,000 ppm (0.1-0.2 volume percent) for certain deposit control additives. Our review of information from the Fuel and Fuel Additives (F&FA) Registration Database revealed that less than one percent of diesel performance additives contain sulfur. Sulfur is present in some of these additives at such low concentrations that their use at manufacturer-recommended treatment levels would have only a very small impact on diesel fuel sulfur content (\ll one ppm). However, we found that certain sulfur-containing performance additives could contribute substantially (by as much as 50 ppm) to the sulfur content of finished diesel fuel when used at the manufacturer-recommended treatment rate. This potential impact on diesel fuel sulfur content is further compounded by the fact that fuel manufacturers sometimes use certain diesel performance additives at treatment rates that are two to three times that recommended by the additive manufacturer and that multiple additives can be added at the same time. Further information from the F&FA database indicates that sulfur containing additives are used by approximately 25 percent of fuel manufacturers.

Our proposal to limit the sulfur content of additives used in diesel fuel to less than 15 ppm would require that the use of certain diesel fuel additives be discontinued. However, our review of the F&FA database indicates that alternative additives that perform the same function and which do not contain sulfur are readily available. This review also showed that the use of diesel additives with a high sulfur content is on the decline. This supports anecdotal information that there is a trend away from the use of diesel additives with a high sulfur content. The above information suggests that discontinuing the use of the limited number of diesel additives with a high sulfur content would not result in significant increased costs or an undue hardship to additive and fuel manufacturers.

In the proposed rule, we requested comment on whether additives not meeting the 15 ppm sulfur cap should be allowed to be added to diesel fuel downstream in de minimis amounts. Several additive manufacturers suggested that rather than placing a cap on the sulfur content of diesel additives, that we limit the contribution to the sulfur content of the finished diesel fuel that results from the additive's use. This might be accomplished by requiring that the concentration at which a fuel manufacturer blends a diesel additive does not exceed the maximum recommended treatment rate which the additive manufacturer attests (in its additive registration under 40 CFR Part 79) will increase the sulfur content of the finished diesel fuel by no more than a prescribed amount (example: 0.1 ppm). Although this approach might provide additive manufacturers with additional flexibility in formulating their additives, it might also necessitate a disproportionately large

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recordkeeping and reporting burden for the industry associated with limiting the concentration at which additives that exceed our proposed sulfur standard are used.^e We believe that this circumstance and indications that the use of diesel additives with a high sulfur content can be discontinued without placing a significant burden on industry is sufficient justification for proposing a 15 ppm cap on the sulfur content to diesel additives. Comments from the NPRM will aid in EPA's further evaluation of which regulatory approach is most appropriate. Of particular interest will be information regarding the difference in price between high-sulfur and low-sulfur additives and whether there are differences in their performance.

2. Potential Contamination in the Distribution System

Each link in the distribution system of highway diesel fuel is a potential source of sulfur contamination. The following diagram of the fuel distribution system illustrates the different pathways that highway diesel fuel can follow from the refinery/importer to the end-user.

^e The gasoline detergent program (40 CFR Part 80) requires the use of a minimum concentration of an approved detergent additive in all gasoline. The detergent program includes a volume accounting reconciliation (VAR) system to help ensure that a sufficient amount of detergent is used. Under this VAR system, detergent blenders must keep records of gasoline and additive volumes used during prescribed intervals and show that the amount of detergent used is above the amount which corresponds to the additive manufacturer's minimum recommended treatment rate. If EPA were to follow the suggested alternative approach, an analogous VAR system might be needed to monitor the use of sulfur-containing diesel additives which do not meet the proposed 15 ppm cap on sulfur content.

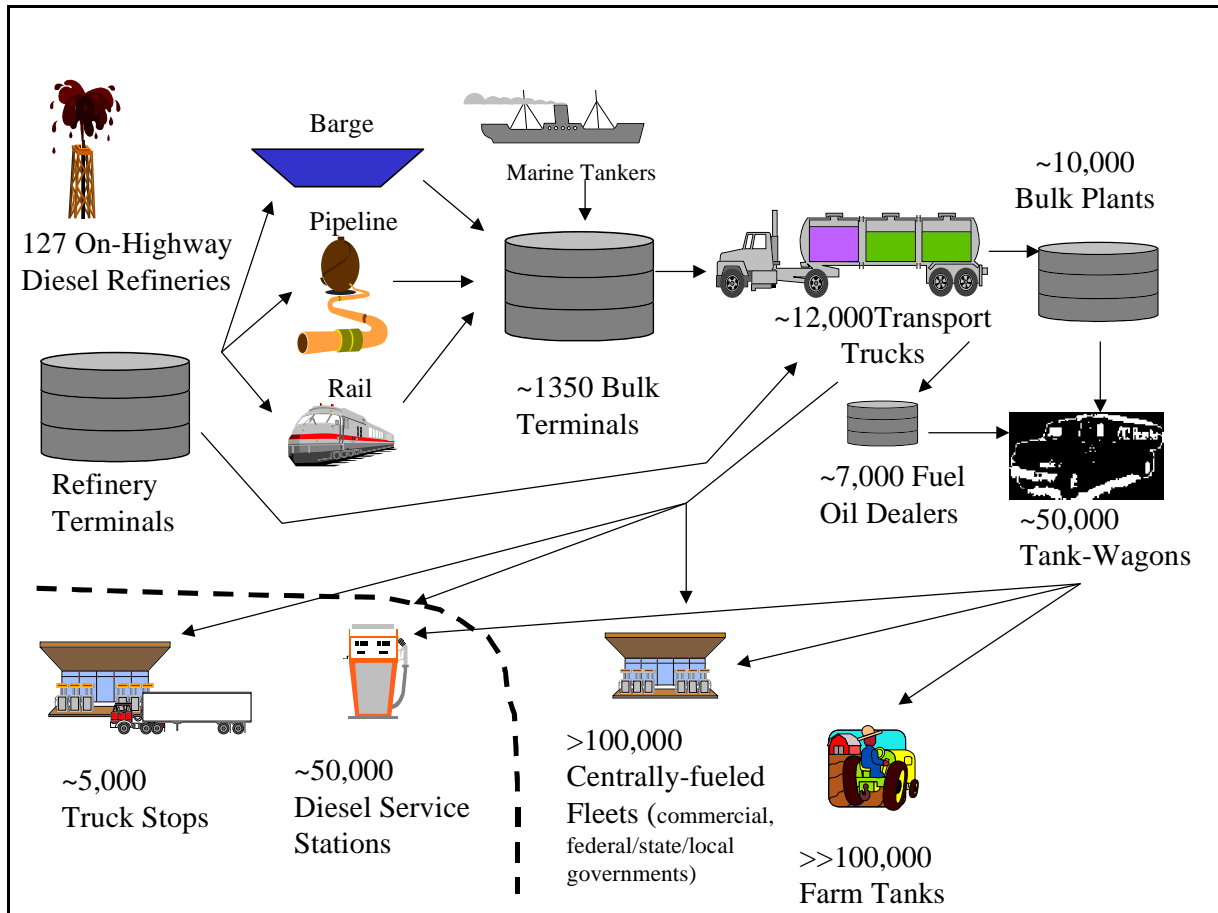


Figure IV-1: Highway Diesel Fuel Distribution System

As illustrated in the preceding diagram, some distribution paths to the end-user have fewer links than others.^f For example, in some cases diesel fuel is shipped by tank-truck directly from the refinery to the end-user. In other cases, the fuel might travel by pipeline to a bulk terminal, then by tank-truck to a bulk plant, then by tank-wagon to the end-user. Thus, there can be as few as a single

^f For the purpose of the discussion in this section, the term end-user is defined as including the retail facility.

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link or as many as five links in the distribution chain from the refinery to the end-user. The sulfur contamination which occurs in each link of the distribution chain is cumulative. Therefore, sulfur contamination could be a more significant concern for distribution pathways with the most links.

Sulfur contamination can occur as the fuel is shipped by pipeline from the refinery to bulk terminal either through mixing with adjacent products in the pipeline which have a higher sulfur content (such as off-highway diesel) or from absorption of sulfur-laden petroleum species deposited on the pipeline walls. The measures that would need to be taken to limit contamination from this source are discussed in more detail in the following section.

Fuel can also be transported from the refinery to the bulk terminal by barge, rail-tanker, or transport trucks. Sulfur contamination can occur during these modes of transportation when the tank compartment used to ship highway diesel was previously used to ship a product with a higher sulfur content. Such contamination can result from mixing with the higher sulfur product that clung to the walls of the tank compartment after the tank was drained (“wall wetting”), or from not draining the tank completely. Our discussions with tank-wagon manufacturers indicate that with careful observation of current industry practices, tanks can be drained completely. Such practices include ensuring that the tank is level, allowing sufficient time for the tank to drain, and purging supply lines of residual product. This should also be true for tank-trucks, since contamination concerns for these two types of vehicles are inherently similar.

We believe that this would also be the case for rail-tankers and fuel barges, and are currently seeking confirmation of this assessment from industry. We do not anticipate that consistently observing current practices to limit contamination would result in increased costs. However, some distributors may find it necessary to reeducate their employees in the importance of their careful observance. Assuming that the compartments are completely drained, we believe that the industry should be able to continue with the current practice of using truck, barge, and rail-car tank compartments to sequentially transport different petroleum products. Although some contamination would be unavoidable from wall-wetting by high-sulfur products, we do not believe that the level of contamination from this source would be substantial enough to necessitate the dedication of tank compartments only for the transportation of highway diesel fuel (or cleaning of tank compartment prior to their use to transport highway diesel fuel).

Based on this assessment, we believe that current industry practices used to prevent contamination during the transportation of petroleum products by marine tanker, if consistently observed, would also be sufficient to limit sulfur contamination and maintain compliance with the proposed sulfur standard. Likewise, we believe that other than for the need for increased quality assurance testing at bulk terminals (discussed in the next section), current industry practices at facilities which temporarily store fuel in stationary tanks (bulk terminals, bulk plants, and fuel-oil dealers) would be sufficient to limit sulfur contamination. This assumption is bolstered by our assessment that storage tanks at such facilities are typically dedicated to contain a single type of petroleum product. We believe that this is also common practice for marine tankers. We believe that increased quality assurance testing at bulk plants and fuel-oil dealers would not be needed as

long as these facilities consistently observe current industry practices to limit contamination.

Our bottom-line assessment is that the sum total level of sulfur contamination for the entire distribution system can be limited sufficiently so as not to interfere with maintaining the proposed sulfur cap throughout the distribution system. If as expected, refiners would produce on highway diesel fuel with a sulfur content of approximately 7 ppm to comply with the proposed sulfur standard and variability in measuring diesel sulfur content is limited to less than +/- 4 ppm, downstream sulfur contamination would need to be limited to less than 3 ppm to comply with the proposed 15 ppm cap. We have not differentiated what levels of contamination might be attributed to each section of the distribution system. We anticipate that comments requested in the NPRM will help to facilitate this task, and help us further evaluate the potential impacts on each segment of the distribution system of limiting sulfur contamination.

As discussed above, we believe that sulfur contamination could be adequately limited in large part by consistent and careful observation of standard industry practices. These practices include the following:

- Properly leveling tank trucks to ensure that they can drain completely of high-sulfur product prior to being filled with the proposed diesel fuel.
- Allowing sufficient time for tanks to drain of high-sulfur product prior to being filled with the proposed fuel.
- Purging delivery hoses of higher sulfur product prior to their use to deliver the proposed fuel.

To adequately limit sulfur contamination, these practices would need to be followed each and every time with adequate care taken to ensure their successful and full completion. We do not anticipate that observation of these practice would necessitate additional actions by industry. However, some distributors may find it necessary to conduct an employee education program to emphasize their importance. The additional measures that we anticipate pipeline and terminal operators would need to take to limit contamination are discussed in the following section. This is followed by additional discussion of potential concerns regarding limiting contamination during shipment by tank-trucks and tank-wagons.

a. Additional Measures by Pipeline and Terminal Operators to Limit Contamination

In discussions with industry, two potential areas where costs might increase for pipeline and terminal operators were identified. First, a batch of highway diesel is usually shouldered with gasoline on one side and kerosene or jet fuel on the other side in the pipeline. In transit some mixing occurs between adjacent fuels at their junction. This mixture is called interface if it can be handled by adding it to another fuel carried by the pipeline. It is called transmix if it must be reprocessed into a marketable product. A mixture of gasoline and diesel must be reprocessed, and thus it is called transmix. There would be no change in the handling of the gasoline/diesel transmix due to the reduced sulfur level, and thus no change in cost. This is due to the fact that limiting the

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contamination of diesel fuel by gasoline is the driving concern.^g A mixture of highway diesel fuel and off-highway diesel fuel, kerosene, or jet fuel is usually added to off-road diesel fuel, and is thus considered interface. The amount of interface required to prevent sulfur contamination of highway diesel is largely determined by the difference in sulfur content with adjacent products in the pipeline.^h Therefore, the amount of interface required to prevent sulfur contamination during pipeline shipments of highway diesel could increase if the proposed sulfur standard is implemented.

The second area where costs might increase is quality assurance testing at the terminal level. Such testing would involve drawing a sample from each batch of on highway diesel fuel and testing (or having a contractor test) the sample for its sulfur content. The potential cost of the increase in pipeline interface volumes and added quality assurance testing at the terminal is estimated in Section V.C.3.

b. Potential Concerns Regarding Delivery by Tank-Trucks and Tank-Wagons

Concerns were raised by the Petroleum Marketers Association of America (PMAA)⁴² that if the contemplated sulfur standards are adopted it would be nearly impossible using current industry practices to meet the proposed sulfur specification for certain small deliveries of highway diesel fuel made by tank-trucks and tank-wagons.

Tank-wagons that operate in the Midwest often have multiple compartments, one for gasoline, one for low-sulfur diesel, and one for off-highway diesel.ⁱ Multiple stops are made by these tank-wagons, with a different product potentially being delivered at each stop. PMAA stated that since such tank-wagons typically rely on a single delivery system (pump, hose, & nozzle) for distillate product delivery, there would be some mixing in the delivery system of the distillate products contained in the different tank-compartments when transitioning from one delivery to the next. To prevent mixing of gasoline with diesel fuel, tank-wagons that deliver gasoline in addition to distillate products typically have a separate fuel delivery system dedicated to the delivery of gasoline.^j PMAA related that the degree of mixing that currently takes place between the deliveries of highway diesel fuel and other distillate products can be tolerated without exceeding the current 500 ppm cap on the sulfur content of highway diesel fuel. However, if the cap was lowered to the level under consideration, the mixing of products that currently takes place might cause the cap to be exceeded. PMAA stated that if this were the case, it would force distributors to change their

^g The addition of gasoline to diesel fuel can cause driveability problems and is a safety concern.

^h Fuel parameters other than sulfur also need to be considered when determining the amount of interface needed between highway diesel and adjacent products in a pipeline shipment.

ⁱ Kerosene or heating oil might also be contained in one of the tank-wagon compartments.

^j Having a separate delivery system for gasoline is desirable because the addition of gasoline to diesel fuel can cause driveability problems and is a safety concern.

delivery practices and/or purchase new equipment to maintain the same level of product delivery.

Under current industry practices, the goal of tank-wagon operators is to minimize the amount of product mixing that takes place by switching the product flow just prior to the end of the delivery so that the delivery system is charged with the product intended for delivery at the next stop. However, PMAA states that this is not always feasible because the receiving tank may fill more quickly than was expected, or the next customer may not need the product that has been put into the hose. PMAA relates that even if good business practices allow the hose to be largely purged, approximately 10 gallons of product flows between the two products in subsequent deliveries. PMAA states that tax regulations for diesel fuel recognize this problem and allow for this type of “misblending”. Based on this, PMAA suggests that EPA consider a *de minimis* blending exemption to cover such circumstances.

In transitioning from the delivery of off-highway diesel to highway diesel, PMAA relates that after switching to highway diesel at the end of the delivery of off-highway diesel, tank-wagon operators typically observe the color of the product being delivered and do not turn off the flow until the stream is clear. Since off-highway diesel (including heating oil) typically contains a red dye, a clear stream indicates that the delivery system is completely flushed of off-highway diesel fuel. To the extent possible, distributors schedule their tank-wagon deliveries so that the deliveries of highway diesel are first. This practice also helps to eliminate contamination concerns. In instances where the delivery system is not properly charged for the delivery of highway diesel (i.e. contains off-highway diesel), tank-wagon operators would purge the fuel contained in the hose back into the off-highway diesel compartment of the tank-wagon.^k This is that current practice and we anticipate this practice will continue. As noted earlier, contamination which occurs when switching the product contained in tank-wagon compartments can be substantially limited by ensuring that the tanks are completely drained (by leveling the tank compartment and allowing sufficient time to drain), and supply lines are completely purged.

As previously discussed, we believe that the proposed sulfur specification must not be exceeded in any part of the distribution system. Any downstream sulfur contamination must be accommodated by the difference between the proposed sulfur cap and the actual sulfur content of diesel fuel produced by the refiner. Our understanding is that cross-product contamination concerns such as those described by PMAA are currently driven and would continue to be driven by the stringency of the Internal Revenue Service (IRS) requirement that highway diesel fuel contain none of the red dye which IRS specifies for use in off-highway diesel fuel to indicate its non-tax status. Unlike EPA’s similar dye requirement, which requires only that no visible evidence of red dye be

^k PMAA relates that operators of tank-wagons with multiple compartments routinely employ this method of purging the off-highway diesel contained in the fuel delivery system. Some tank-wagons are loaded from the top and others are bottom loaded. The purging of off-highway diesel contained in the delivery system back into the off-highway diesel compartment is less convenient for top-loading tanks and there is a safety concern with this process. However, since such purging is current industry practice, we do not anticipate that the proposed sulfur requirements would place an additional burden on industry regardless of whether top or bottom loading tank wagons are used.

present in highway diesel fuel, the IRS requirement can be enforced by conducting a chemical analysis of the fuel to identify whether the red dye is present. The presence of an extremely small quantity of dye can cause a failure of EPA's visibility-based requirement, while an even smaller quantity can cause a failure of IRS chemical-based requirement. Therefore, a fuel that passes these dye requirements, might also be judged to have not suffered substantial sulfur contamination from off-highway diesel fuel. Current industry compliance with both the EPA and IRS dye requirements indicates that sulfur contamination can be adequately limited during shipment by tank-wagon using the current practices described in this section. Consequently, EPA believes that the proposed sulfur standards would not disrupt the distribution of highway diesel by tank-wagon, or significantly increase the cost of such deliveries. Since contamination concerns related to shipment by tank-truck are fundamentally the same as those for tank-wagons, we believe that the same conclusion would be applicable regarding the distribution of diesel fuel by tank-truck. We anticipate comments on the NPRM will help us to further evaluate the potential impacts on tank wagon and tank truck operators of limiting sulfur contamination under the proposed rule.

3. European Experience With Low-Sulfur Diesel in the Distribution System

The European experience in limiting sulfur contamination of low-sulfur diesel fuel in the distribution system may help to inform our evaluation regarding the feasibility and costs of maintaining low-sulfur diesel fuel in the U.S. distribution system. European Union countries will limit sulfur in diesel fuel to 50 ppm by 2005, and proposals to require even lower levels are being discussed. We are seeking input on issues that the European Union has encountered in its evaluation of the difficulty of limiting the sulfur contamination in the distribution system.

One European country has had extensive experience with the transition to low sulfur diesel fuel. In the early 1990's, Sweden decided to take advantage of the environmental benefits of 10 ppm sulfur/low aromatics fuel by introducing it with a reduction in the diesel fuel tax. The program has been quite successful, and in excess of 90 percent of the road fuel used there is of this 10 ppm sulfur class.⁴³

The ability of the Swedish fuel distributors to maintain these low sulfur levels throughout the distribution system to the end-user has apparently been quite good. A sulfur-level test program conducted on Swedish diesel fuel several years ago at 150 fuel stations found no sulfur levels out of the specification. Authorities in Sweden feel that competitive forces help maintain compliance. However, it should be noted that at-pump compliance with the sulfur specification is aided by the fact that the home heating fuel (2000 ppm sulfur) distribution system is separate from the on- and off-highway fuel distribution system. Further, the sales of higher sulfur diesel fuels in Sweden are very low (less than 10 percent of the total) and their sulfur levels are low relative to U.S. fuels: 50 and 500 ppm for higher-sulfur highway and off-highway fuels, respectively, compared to 500 and over 2,000 ppm in the U.S. Thus the potential for contamination is significantly less in Sweden.

Chapter IV: Fuel Standard Feasibility

Nevertheless, the Swedish experience and the plans of the European Union may lend some support to our assessment that the contamination of low-sulfur highway diesel fuel can be successfully limited by the U.S. distribution system without undue hardship.

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42. Comments of the Petroleum Marketers Association of America (PMAA) on the Diesel Fuel Advance Notice of Proposed Rulemaking (ANPRM), Docket A-99-06, Item II-D-73.
43. Memo from Thomas M. Baines to Docket A-99-06, October 29, 1999, Docket A-99-06, Item II-G-12.

