OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2009/093

Third-Party Evaluation of PetroTex Hydrocarbons, LLC., ReGen™ Lubricating Oil Re-Refining Process

March 2009

Prepared by
A. L. Compere
W. L. Griffith

UT-BATTELLE

ORNL-27 (4-00)

ORNL/TM-2009/093

Prepared under Contract No. NRE-08-01311

Third-Party Evaluation of PetroTex Hydrocarbons, LLC., ReGen™ Lubricating Oil Re-Refining Process

A. L. Compere
W. L. Griffith

Date Published: March 2009

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

EXECUTIVE SUMMARY

This report presents an assessment of the PetroTex Hydrocarbons, LLC., ReGen™ process for re-refining used lubricating oil to produce Group I, II, and III base oils, diesel fuel, and asphalt. PetroTex Hydrocarbons, LLC., has performed extensive pilot scale evaluations, computer simulations, and market studies of this process and is presently evaluating construction of a 23 million gallon per year industrial-scale plant at a site in Midlothian, Texas. PetroTex has obtained a 30 acre site in the Texas Industries RailPark in Midlothian Texas. The environmental and civil engineering assessments of the site are completed, and the company has been granted a special use permit from the City of Midlothian and air emissions permits for the Texas Commission on Environmental Quality.

The impact of constructing these facilities on local employment is significant. If the plant size remains constant, each plant could create 1400 construction jobs and employ a permanent staff of 28. Additionally, transportation of used oil to the re-refinery will require approximately 12 truck drivers.

Flexibility gives the ReGen™ process higher returns on investment and shorter payout times in comparison to a recent analysis of worldwide oil re-refining processes performed by Audibert (2006). More importantly, results of a sensitivity analysis conducted by PetroTex Hydrocarbons, LLC., to evaluate variation in payout time with crude oil price showed that, unless the crude oil price remains below $50 per barrel for extended periods, payout times are less than two years. The PetroTex process analysis showed a profit down to a crude price of about $21/barrel. The ability to operate profitably across a wide range of crude oil prices is important because the price of base oils is typically correlated with that of crude oil and the price of crude oil has remained extremely volatile since 2001.

There is an excellent chance that the PetroTex Hydrocarbons, LLC., ReGen™ re-refining process will be successful. The major reasons for this are its process flexibility, high process integration. The ReGen™ process also provides high energy yields in the forms of process and marketable fuels, as well as a high yield of at least two grades of base oils from the used oil. The process was developed to minimize purchased process energy.

There are several factors which would encourage PetroTex Hydrocarbons, LLC., to build their proposed plant:

1. The market for the base oils which are blended with additives to manufacture the lubricating oils used in transportation and in industrial processes is large by chemical process standards. For example, sales of lubricants in the U.S. were above $10 Billion in 2005 and many of the establishments which produce lubricants purchase, rather than manufacture, the base oils from which they are blended.

2. The success of a limited number of industrial scale competing processes has established the utility of re-refined base oils in conventional transportation lubricants and has also shown that re-refining lubrication base oils is acceptable to customers and is also typically profitable.

3. As a result of Executive Order 13423, the federal government is required to establish "closed-loop recycling" programs in which the base oils in transportation lubricants are recovered, re-refined, and recycled back into transportation lubricants. This creates

a significant incentive for development and deployment of processes which provide high quality oil blending bases. The Department of Defense has also developed standards for re-refined base oils and lubricants and has shown them to be equivalent to products from virgin oil. The Defense Logistics Agency, on behalf of the Department of Defense, collects used oil for re-refining and re-blending. It is also willing to sell this material to other government agencies (most notably the U.S. Postal Service) and their contractors.

4. In addition to requiring federal agencies and their contractors to purchase re-refined and recycled products, Executive Order 13423 requires all federal agencies and their contractors to reduce their consumption of non-recycled petroleum products by 2% per year; and 3) relative to 2003, requires a 30% reduction in energy intensity by 2015 (or a 3% reduction in energy intensity per year relative to 2003, reaching 30% reduction by 2015).

5. In 2008, the Environmental Protection Agency issued rule EPA503-F-08-006. This excludes used lubricants from being considered as solid wastes under the Resource Conservation and Recovery Act if used oil is being collected or transported with intention of closed-loop recycling. This means that, barring evidence to the contrary, used oil can be treated as a non-hazardous material. As this decision went into place at the end of 2008, the rule specifically classifies used oil intended for combustion as a solid waste. This ruling, which is essentially a culmination of two decades of Environmental Protection Agency support for oil recycle and re-refining was passed because re-refining, as opposed to combustion, of used oil is environmentally beneficial and could reduce greenhouse gas emissions and minimize improper disposition of used oil.

6. Other federal regulations are, for the most part, extremely favorable to use of re-refined of transportation lubricating oil. A 2007 presidential executive order requires all federal agencies and their contractors to preferentially purchase re-refined oil and other recycled products (without consideration of cost or substantial equality).

7. The proposed construction of the Midlothian facility has been estimated to create 1400 jobs and operation to require a staff of 28. It will also be served by at least 12 truck drivers. The jobs created per dollar invested significantly exceed the requirements for the federal stimulus program.

The used transportation oil re-refining processes currently fielded at industrial scale are, with one exception, based on the Mohawk process developed in the 1980s. These processes are relatively straightforward and have been used by Evergreen Oil, Inc. and Safety-Kleen for two decades. A new plant, based on the simplified Mohawk-Evergreen process and constructed by Heartland Petroleum to treat the waste oil from the Lube Stop chain has found good customer acceptance of lubricating oils with a high recycled content. The Lube Stop chain has been able to charge a premium for its re-refined oil products.

Re-refining of used domestic oil is expected to increase in the next decade. There are several reasons for this. As discussed above, there are a number of environmental advantages to recycling. However, it is also important to remember that petroleum refiners recover less than 1% of incoming crude oil as base oils. If trends continue, the U.S. will expect to import a larger fraction of its petroleum in a refined form. Any base oils would need to be recovered by the foreign producer and would be expected to carry a premium above the cost of crude oil.

Refining waste oil in the U.S. decreases the need to purchase foreign-produced base oils and, additionally, creates domestic jobs.

Use of re-refined base oils could also minimize both energy and greenhouse gases emissions. Safety-Kleen, a Chicago producer of re-refined base oils, estimates that every 100 million gallons of re-refined lubricant base oil is the equivalent of taking 200,000 cars off the road. Burning, rather than re-refining, is the major current use for waste lubricating oils. However, combustion of 100 million gallons of base oil, by Safety-Kleen's estimate, emits 300,000 metric tons of greenhouse gases. Re-refining minimizes greenhouse gas emissions by both decreasing the energy required to produce oil and providing an alternative to burning used oil.

By its structure, the conventional lubricant market encourages the use of re-refined base oils in a number of ways. Most of the manufacturers are small businesses which purchase and blend base oils and additives. Feedstock materials, comprised primarily of base lubes, are the largest lubricant manufacturing cost. Wages are the smallest. There is considerable variation in the profitability of lubricant manufacture, with manufacturers in Louisiana, Texas, Pennsylvania, and Kansas producing more than a million dollars of shipped product per employee per year (2004). The diversity and profitability of lubricant manufacture both prevent market domination by a limited number of large companies and encourage the use of recycled and re-refined base oils in finished products.

ABSTRACT

This report presents an assessment of market, energy impact, and utility of the PetroTex Hydrocarbons, LLC., ReGen™ process for re-refining used lubricating oil to produce Group I, II, and III base oils, diesel fuel, and asphalt. PetroTex Hydrocarbons, LLC., has performed extensive pilot scale evaluations, computer simulations, and market studies of this process and is presently evaluating construction of a 23 million gallon per year industrial-scale plant. PetroTex has obtained a 30 acre site in the Texas Industries RailPark in Midlothian Texas. The environmental and civil engineering assessments of the site are completed, and the company has been granted a special use permit from the City of Midlothian and air emissions permits for the Texas Commission on Environmental Quality.

1. INTRODUCTION

This report presents a preliminary assessment of the new PetroTex Hydrocarbons, LLC., ReGen™ process for re-refining used transportation lubricants into base oils and byproducts (asphalt, diesel fuel, process energy). Lubricants are typically manufactured by blending together an additive package and a base oil. At present, most of the base oils used in the U.S. are produced from virgin petroleum using a process which is described as "among the most energy intensive refinery processes" (Office of Fossil Energy 2006). To prevent pollution, used transportation lubricants are collected. However, only three domestic manufacturers offer "closed-loop recycle" in which the base oils, which are the major constituents of lubricating oil, are recycled back into lubricating oil.

In late December, 2008, the Environmental Protection Agency, issued a new definition of solid waste in which used oil destined for re-refining is not classified as a solid waste because re-refined base oil can be repeatedly recycled into a product equal to that from which it was derived. The rule both applies to the entire used oil collection and transportation process and, for re-refined transportation lubricants, also provides some protection against Superfund liability.

This is different from the most common current recycle processes in which used transportation oil is collected for use as an industrial fuel (single-use recycle) or is converted to a less-recyclable industrial oil (downward recycling or downcycling). Used oil destined to be used as fuel or oil is now classified as a solid waste. The same definition applies to the collection, transportation, and recycling processes which precede the combustion use of the oil or which involve the production of a downcycled oil.

It is expected that the new Environmental Protection Agency rule will strongly encourage re-refining of used transportation oil.

Section 2 covers the market for domestic lubricating oil. It includes historical data on sales, fraction of refinery output, costs, and workers. Use by sector is also included in this section, as are the prices of American Petroleum Institute Group I, Group II, Group II+, and Group III base oils. The flexibility and integration of the lubricant market are evaluated, as they will have a significant impact on the ability to introduce new technologies. The market for used transportation lubricants, in terms of volume, is also briefly discussed, as are the normal reported costs incurred in blending lubricants.

Section 3 evaluates conventional processes for production of base oils in a petroleum refinery. It also discusses the history and development of processes for re-refining of used lubricants in the U.S. and other countries. Major processes that have been used across the last four decades, together with processes which are now at the pilot development stage, are detailed. The major industrial scale processes for re-refining of used transportation oil in the U.S. are reviewed and details of their processes and product flow are discussed. Particular features of their markets are profiled.

Section 4 assesses the PetroTex Hydrocarbons, LLC., ReGen™ process for used oil re-refining. This process is capable of treating used transportation lubricants to recover both Group I and Group II base oils using an advanced technology based on conventional chemical refining. The readiness of the process for commercialization is assessed using a stage and gate system which has become standard in several Department of Energy programs. The process equipment is detailed and its functions are reviewed. Comparative economics for both the ReGen™ process and for full scale industrial processes for used oil re-refining are evaluated in terms of capacities, capital costs, profit, depreciation, rate of return, and pay-out period. This is done in a standardized way to permit direct comparison of the processes. In light of recent crude oil price volatility, the sensitivity of pay-out periods to the price of crude oil is evaluated. The treatment of intellectual property in the field is evaluated and the implications of the PetroTex Hydrocarbons, LLC., ReGen™ process discussed. The jobs which would be created by the planned construction and operation of the PetroTex Hydrocarbons, LLC., Midlothian facility are evaluated.

Section 5 discusses the national energy and market impacts of in terms of the energy used and materials produced in the conventional refinery and in re-refining processes. National lubricant production in terms of energy content is profiled. Energy required to re-refine used transportation lubricants is evaluated. The energy and volumes of domestic transportation oils are profiled and likely markets evaluated. Market response to recycled lubricating oils is assessed. Current substitutability of re-refined oils for conventionally produced base oils is assessed in terms of meeting engine and professional association specifications. Consumer acceptance is evaluated. The energy benefits of re-refining lubricating oils, which are strong functions of the energy content of the oils as well as process energy, are profiled and extended to estimate national impact of this new energy technology. Greenhouse gas reductions arising from re-refining are also discussed.

Section 6 discusses the impact of federal and state regulations, as well as greenhouse gas production. Used oil recycle is, to a large extent, driven by federal, state, and local laws, regulations, fees, and taxes. Some of these regulations, such as preferential purchase and use of closed-loop recycled products greatly encourage the re-refining of used transportation oils. Other regulations, such as requirements that used motor oils be tested for a wide variety of potentially hazardous materials and that they be handled as hazardous materials, add to the cost of recycling used oil. Although the number of regulations that states have developed to control used oil make it difficult to develop a consistent picture of this area, the impacts of selected federal and state regulations are discussed.

Section 7 presents the report's conclusions.

The findings of this report are also presented in an executive summary and abstract. A bibliography is provided for further information.

2. IS THE U.S. LUBRICANT MARKET LARGE AND BROAD ENOUGH TO SUPPORT INVESTMENTS IN NEW TECHNOLOGY?

Lubricants, although a tiny fraction of total petroleum refinery products, accounted for more than 10 billion dollars in 2005 (Census Bureau 2007). Producers of lubricating oil typically formulate their product by blending an oil stock, or base, with a preformulated additive mixture. The resulting product is then evaluated, packaged for sale, and distributed. The PetroTex Hydrocarbons, LLC., ReGen™ process produces re-refined base oils comparable to those produced from virgin petroleum during conventional refining. These can be substituted for or blended with conventionally produced oil base stocks. The size, history, value, distribution, location, and major uses, of the lubricant market are profiled below.

2.1 CONVENTIONAL VIRGIN LUBRICANT MARKET

As shown in Figure 2.1, U.S. lubricating oil production increased from 40 to 50 million barrels per year between 1950 and 2007 (50 million barrels in 2006) with the exception of a production spike to roughly 65 million barrels per year in the late 1970s. However, lubricants, relative to total refinery output, have decreased from 1.65 to 0.65% across the same period, as shown in Figure 2.2. As shown in Figure 2.3, wages and materials accounted for roughly half of the value of product shipments. Processing, packaging, distribution, and marketing costs, which rose rapidly across the last decade, added cost approximating half that of the finished product. From 1997 to 2005, total employment ranged between 9,500 and 11,400 employees, as shown in Figure 2.4. Production employees were roughly half of total employees.

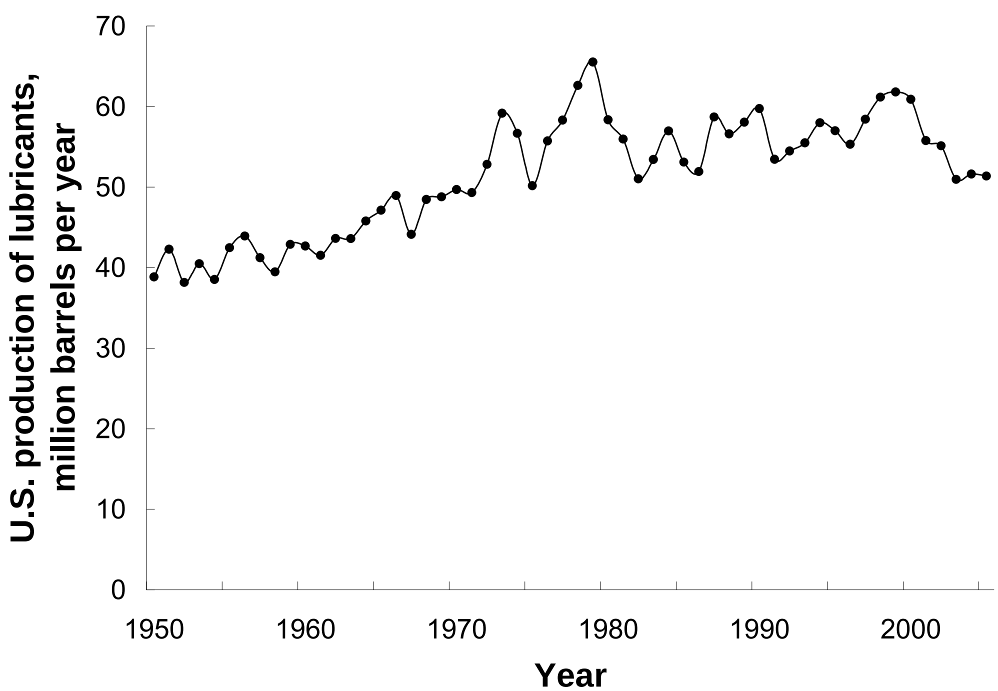

Fig. 2.1. U.S. production of lubricants. Adapted from Energy Information Administration, 2008.

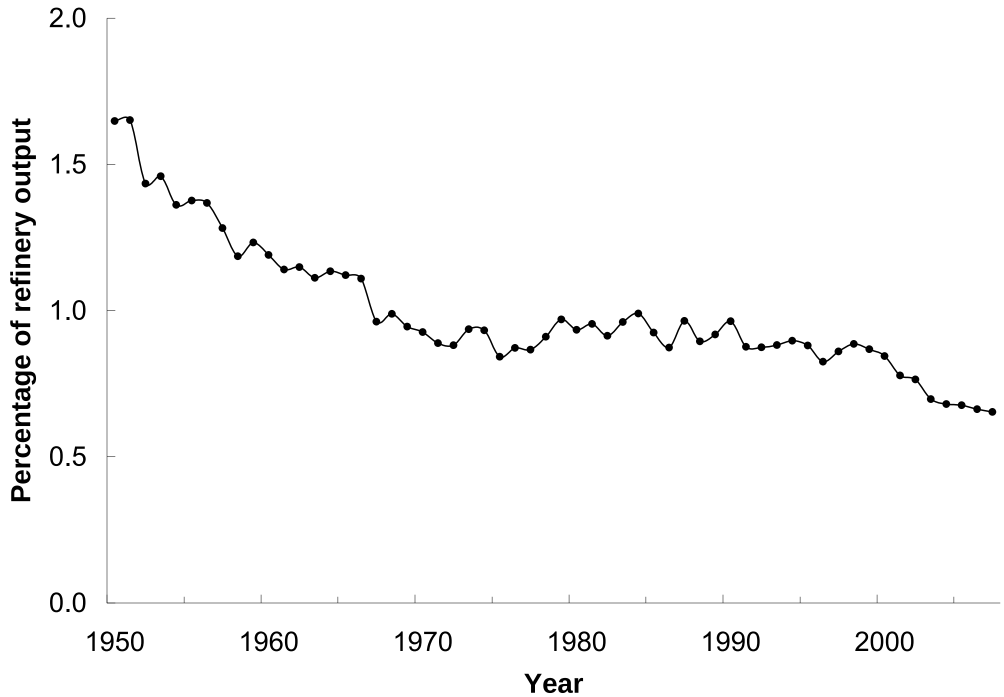

Fig. 2.2. Lubricants as a percentage of U.S. refinery products. Adapted from Energy Information Administration, 2008.

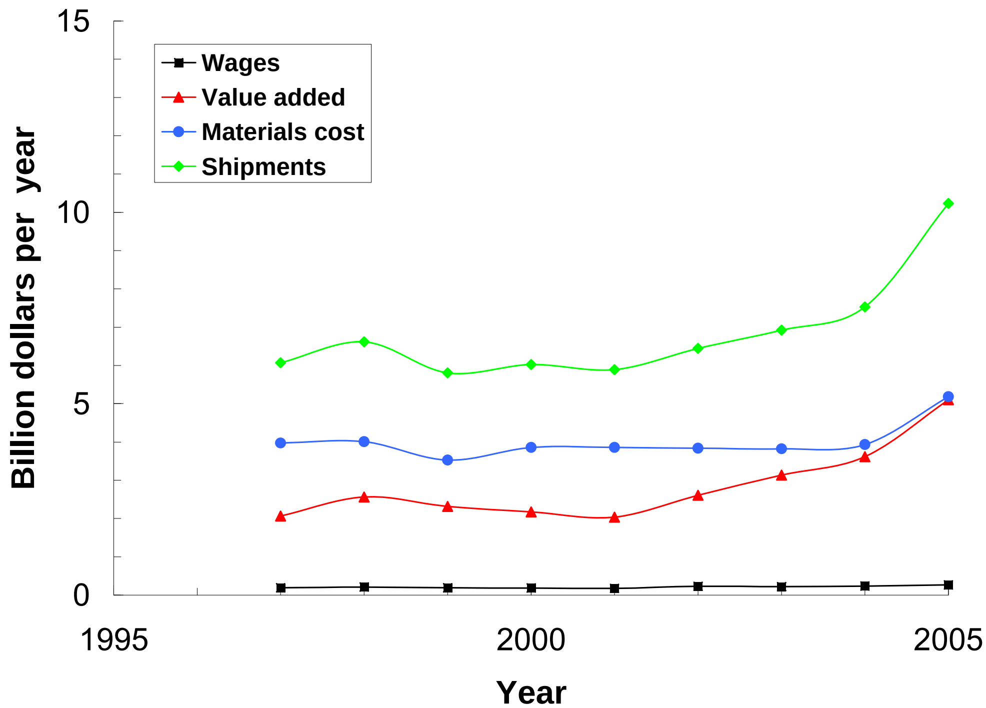

Fig. 2.3. Cost of production and value of U.S. lubricating oil shipments. Adapted from Census Bureau, 2002 and 2006.

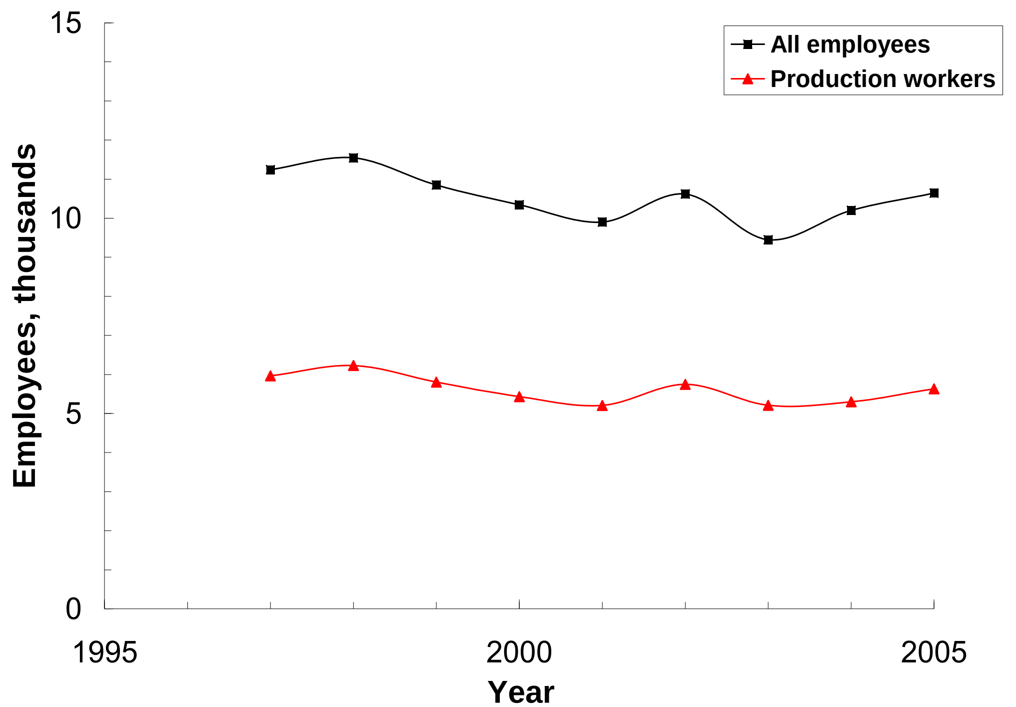

Fig. 2.4. Workers employed in producing U.S. lubricating oil. Adapted from Census Bureau, 2002 and 2006.

This is consistent with normal refinery practice and that of most small specialty chemical companies. However, the contribution of wages to lubricant production cost is low because an average production worker produces roughly $1.8 million of lubricant shipments per year.

Most of the manufactures producing lubricants are classified as small businesses because they have fewer than 500 total employees. Manufactures with 20 to 249 employees had the highest shipments during 2002, over one million dollars per employee per year, as shown in Figure 2.5. Significantly smaller and larger manufactures have lower shipments per employee per year. As discussed earlier, materials cost is the largest expense, and wages represent a very small fraction of total production costs.

Figure 2.6 shows shipments and costs for manufactures in the seven states with the highest production in order of the value of their 2002 lubricant shipments. There is considerable variation in the values of shipments and in materials costs, typically the highest production cost, by state. Wages and capital expenses are the lowest costs.

As shown in Figure 2.7, transportation and industrial use account for most of the lubricants used in the U.S. Since 1965, both sectors have remained comparable in size. Industrial lubricants, as classed by the Energy Information Administration, include hydraulic oils and cutting oils. A limited amount of industrial oils are recycled or rerefined (Section 3). Recycle could be particularly attractive to industry in areas where disposal costs for oils are high and accrue to the producing industry or where lubricants are expensive. With careful selection of industrial contributors and some additional process studies, some industrial lubricants could represent an attractive source of feedstock.

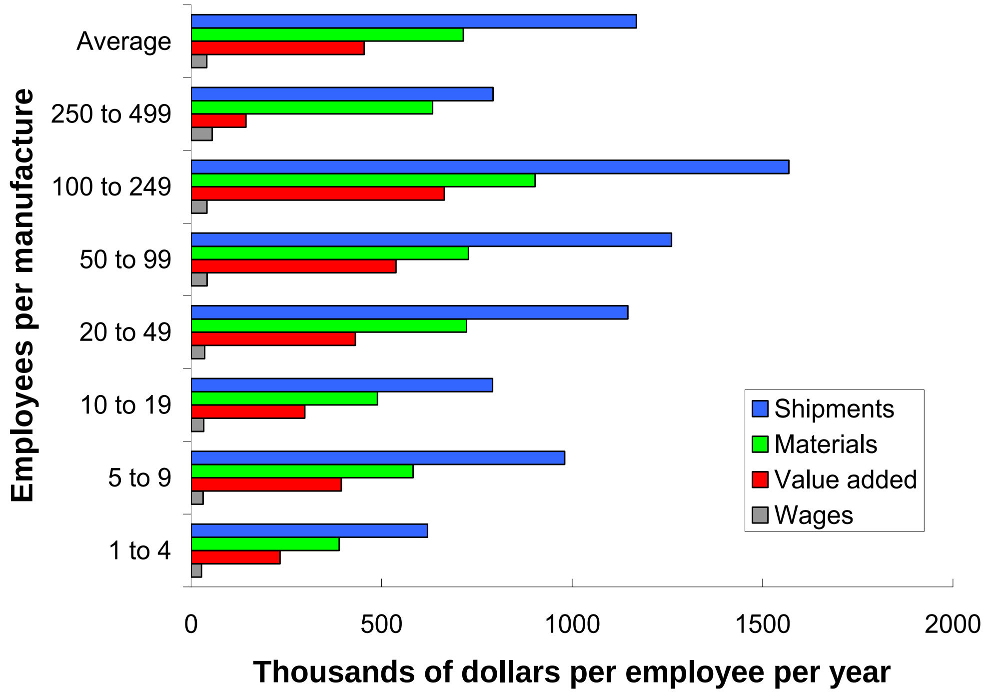

Fig. 2.5. Cost of production and value of shipments per employee by size of U.S. lubricating oil manufacture. Adapted from Census Bureau 2004b.

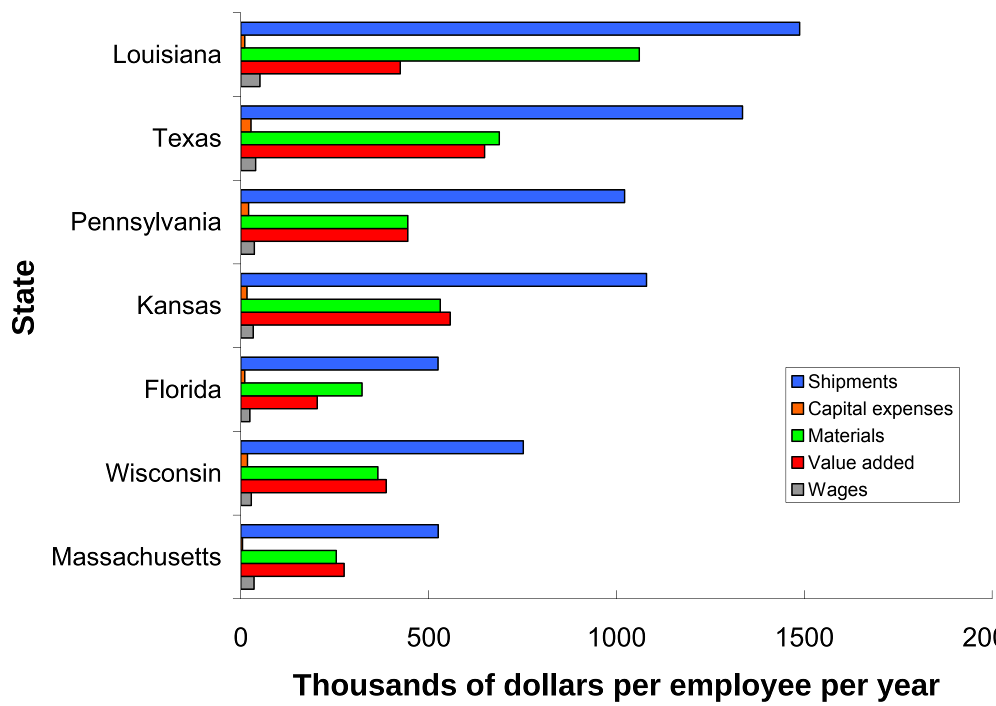

Fig. 2.6. Cost of production and value of shipments per employee by state. Adapted from Census Bureau 2004b.

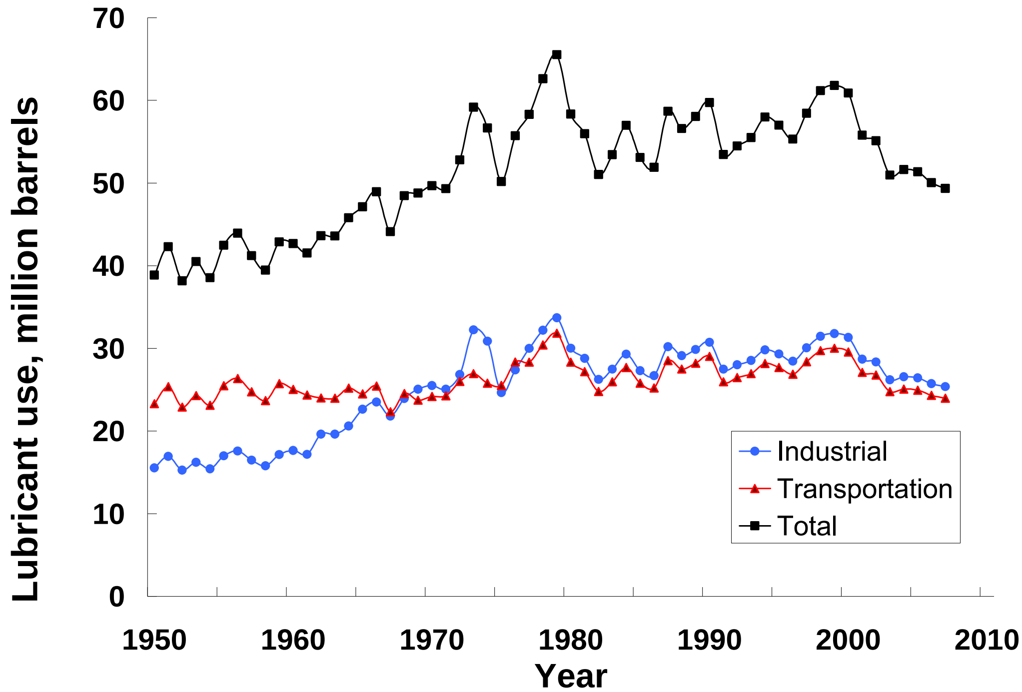

Fig. 2.7. Lubricant use in U.S. transportation and industrial sectors. Adapted from Energy Information Administration, 2008.

2.2 PRICES OF LUBRICANT BLENDING BASE OILS

A number of different lubricant blending bases are manufactured in quantity and sold on the international open market at different prices. Typically, manufactures combine lubricant blending bases with an additive package to produce a lubricant product. The 2001 to 2008 year-end high and low published prices for Group I, Group II, Group II+, and Group III bases are shown in Figures 2.8 to 2.11, respectively. End of year crude oil prices for the period are also shown in Figure 2.8. Data for 2008 are through December 30, the last date for which data were available. Base oils for all but Group III are derived from published or secondary prices of several large international petroleum producers. Prices for only two Group III and one Group III+ producers were available through *Lube Report* data, although this Group appears to be increasing in use.

The price of Group I base oils, as expected, rose with the price of crude oil and remained well above the price of crude oil. The 2008 data shows a continuing rise in Group I and base oil prices and a decrease in the price of crude oil. The drop in the price of crude oil has occurred primarily within the last half of the year and is not yet reflected in the price of base oils. Additionally, the price of lubricants can be affected by production factors, inventory, driving patterns, and the relative value of international currencies.

The price patterns for Group II and Group II+ base oils are very similar to that of Group I base oil: rising with and remaining well above the price of crude oil. Although less data is available for Group III base oils, they appear to be following a similar pattern. At this time, Group III+ oils, at $244/barrel, command a premium over Group III base oils.

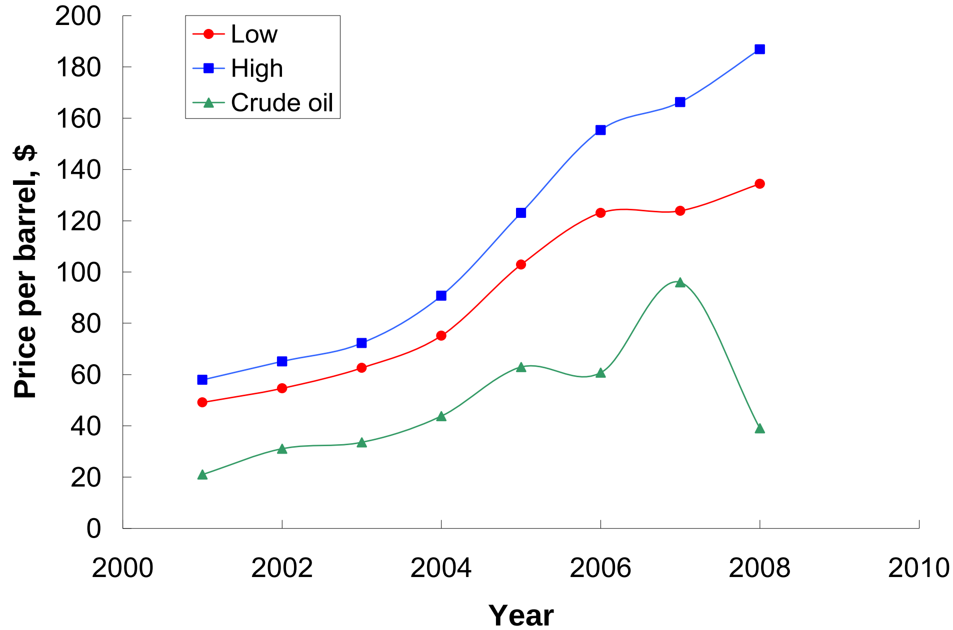

Fig. 2.8. Low and high year-end prices for Group I lubricant base oils and crude oil. Adapted from Sullivan 2002-2007and Green 2008a,b.

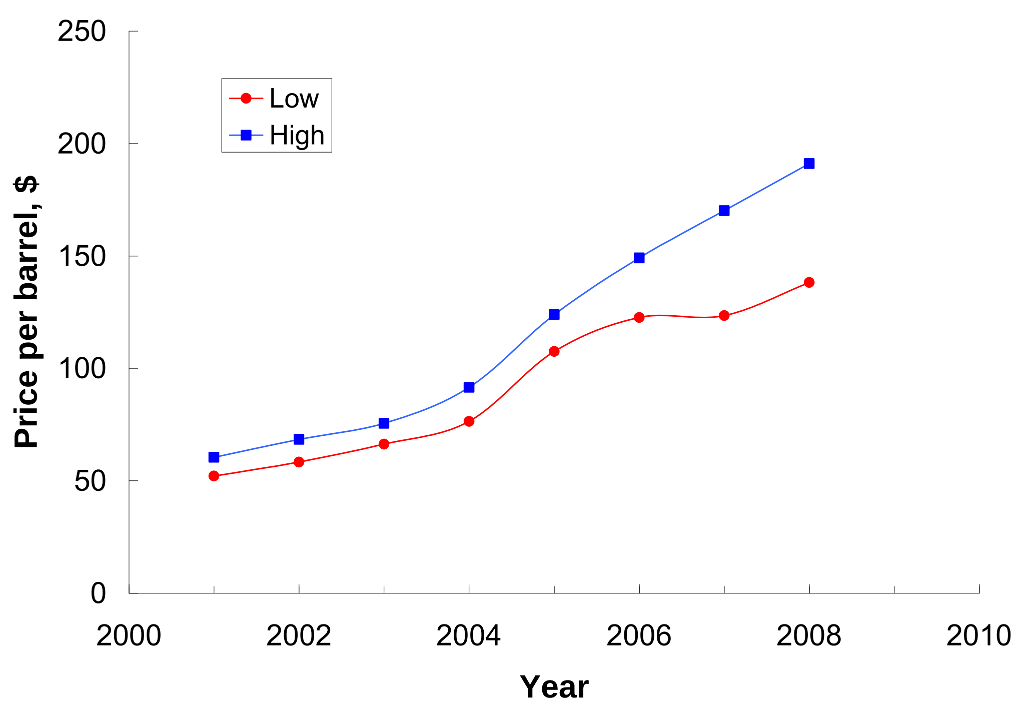

Fig. 2.9. Low and high year-end prices for Group II lubricant bases. Adapted from Sullivan 2002-2007and Green 2008a,b.

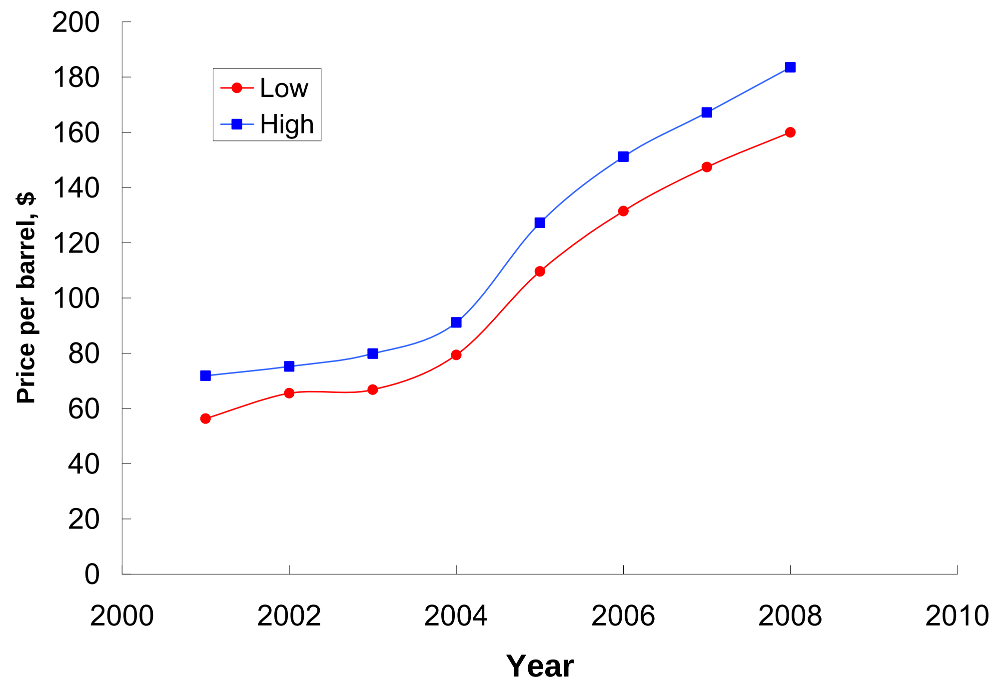

Fig. 2.10. Low and high year-end prices for Group II+ lubricant base oils. Adapted from Sullivan 2002-2007and Green 2008a,b.

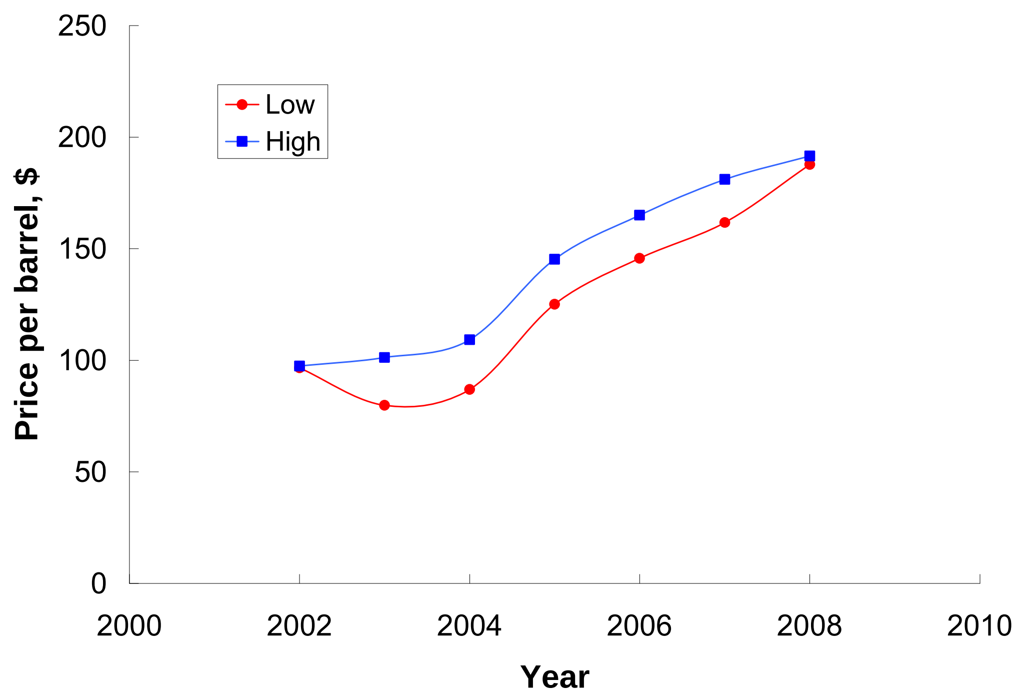

Fig. 2.11. Low and high year-end prices for Group III lubricant bases. Adapted from Sullivan 2002-2007and Green 2008a,b.

2.3 WASTE OIL VOLUMES AND RECOVERY

As discussed earlier, comparable volumes of industrial and transportation lubricants are produced and used in the U.S. The volumes of waste oil collected for reuse vary considerably by state. The different state collection, aggregation, and reporting requirements also make it difficult to ensure that the data obtained reflect actual practice. However, as is evident from large market reviews (Office of Fossil Energy 2006, Lawrence Livermore National Laboratory 2008), a significantly higher fraction of used transportation lubricants than industrial lubricants are collected as waste oil.

The Office of Fossil Energy (2006) estimated U.S. lubricating oil purchases as 56 million barrels per year. Of this oil, 10 million barrels (18%) are improperly disposed, leading to a variety of environmental problems; 23.6 million barrels, consumed (42% - includes combustion and operating loss); and 22.5 million barrels (40%), recovered. Re-refining comprises only 17%, or 4 million barrels per year, of the recovered oil. The balance of recovered lubricating oil is used primarily to fuel asphalt plants (31%), space heaters (12%), industrial and utility boilers (18%), steel mills (8%), and cement kilns (3%).

In practical terms, this means that more than 10, and possibly more than 15, million barrels of waste lubricating oil per year could be re-refined and recycled into transportation lubricants. This amount of re-refined lubricating oil is a multibillion dollar annual market and, if it can be economically collected, is enough to support many regional re-refineries.

As detailed in the Lawrence Livermore National Laboratory study for the California Integrated Waste Management Board, re-refining is the “highest and best use” of lubricant base oils because it recovers a significant fraction of waste oil as property-compatible lubricant base oil (closed-loop recycling). The State of California is considering methods to increase the amount of lubricating base oil produced from waste transportation lubricants. Section 6 discusses the impact of federal and state regulations on used oil re-refining.

2.4 POSSIBLE LIMITATIONS ON USE OF RE-REFINED TRANSPORTATION AND INDUSTRIAL LUBRICANTS

Increasing quality requirements, primarily due to changes in automotive standards, and overall market recycling opportunities may limit production and use of re-refined transportation lubricants.

First, increasing automotive fuel efficiency and performance standards, together with the increased performance available with synthetic lubricants, are gradually increasing the quality of available transportation lubricants. Early re-refining processes (Audibert 2006) are able to produce Group I base oils. However, as discussed in the Fossil Energy report (2006), Group II and higher oils are increasingly required for new vehicles and new applications.

With increasing quality requirements for base oils, newer re-refining processes that can be adapted to produce Group II and “synthetic-equivalent” base oils are likely to have a competitive advantage. Additionally, as base oils are recycled, they become more fully saturated and contain fewer aromatic contaminants with each cycle.

Second, lubricant base oils are used in a wide variety of different formulations applications. At present, transportation oils account for almost all collected and recycled waste oil. Although in 2006 there was some doubt, at present, re-refining of waste transportation oils has been judged by the Environmental Protection Agency (2008) to provide "closed-loop" recycle. That is to say, a product, Group I base oil, is recycled and reused as Group I base oil. The process is acceptable to consumers. It may also be possible to re-refine an increasing fraction of industrial lubricants.

Modern processing technologies, which will be discussed later, do provide methods for making Group II (and higher) base oils.

2.5 THE LUBRICANT MARKET SUPPORTS THE DEVELOPMENT AND DEPLOYMENT OF LUBRICANT RECYCLING AND RE-REFINING PROCESSES

Several conclusions relative to the attractiveness of recycling and upgrading lubricants, in terms of the lubricant market, can be drawn from these data.

1. Over half of the production cost for virgin lubricants produced in petroleum refineries remains the cost of the starting materials themselves. In most cases, materials cost was the dominant cost. Table 2.1 shows costs for several classes of production materials. Materials from petroleum refineries and lube manufacturers account for nearly half of total materials costs. This favors the development of re-refining and recycling technology because reprocessed oil is likely to be competitive with and less expensive than virgin oil stock. Table 2.1 also shows that lubricant manufactures routinely purchase a wide variety of materials from a large number of suppliers.

Table 2.1. Materials consumed in manufacture of lubricants[a]

		Cost, $million	
Material	**NAICS Code**	**1997**	**2002**
Domestic crude petroleum, including lease condensate	21111103	143	149
Additives including antioxidants, antiknock, inhibitors	32500017	44	210
Other additives including soaps and detergents	32500019	437	123
Animal and vegetable oils	31100013	130	
Sodium hydroxide, as 100%	32518107	10	2
Sulfuric acid, excluding spent, as 100%	32518805	5	
Metal containers	33240000	76	45
Plastic containers	32610029		114
Paper and paperboard containers	32220015	58	44
Fiber cans	32221400	28	3
Cost of materials received from petroleum refiners and lube manufacturers	32410007	1362	1766
All other materials, components, and supplies	00970099	637	745
Materials, ingredients, containers, and supplies, nsk	00971000	762	380
Total materials consumed in manufacture of lubricants		3693	3701

[a]Source: 2002 Economic Census

Although lubricant production has slowly increased, lubricants, as a fraction of refinery output, have decreased across the last half century. This is likely due to a number of different factors, including longer times between oil changes, import of refined petroleum products, and re-refining. However, it does indicate that re-refining has potential value in stretching an increasingly limited resource.

2. The U.S. lubricant manufacture market is comprised of more than 400 enterprises that produce a wide range of products. Most lubricant manufactures are small businesses which typically use purchased lubricant base oils to produce a wide range of products. The large number of customers should both favor the development of new technologies and, additionally, make it possible to market a range of process products and byproducts.

3. The size of the U.S. lubricant market, which was more than $10 billion in 2005, is sufficient to support the growth and deployment of a significant number of processing facilities. This is important because the potential returns from business development and process refinement will encourage investment in new technologies.

4. With few exceptions, the year-end prices of all five of the major classes of blending bases have risen consistently, and remained well above the price of crude oil, since 2001. These oils are supplied by a number of manufacturers in many locations. As recyclers demonstrate that the quality of re-refined oils is comparable to (or better than) that of base oils produced from virgin petroleum, they should find acceptance in the broad and diverse base oil market.

The following section evaluates technologies for re-refining used oil. Most of the technologies discussed have been fielded at industrial scale, although a few are still at pilot scale.

3. CONVENTIONAL BASE OIL PRODUCTION, USED OIL RECOVERY, AND RE-REFINING PROCESSES AND TREATMENTS

Lubricating oil blending base can be produced directly from petroleum feedstock in a conventional refinery. It can also be recovered and re-refined from used oil. This section discusses the processes which are used both to produce conventional virgin lubricating oil base and to recycle and re-refine used lubricating oil as base oil. Each of the industrial scale process trains discussed below has advantages and disadvantages, but all of them are capable of producing base oils used to blend lubricating oils. Because waste oil recycle processes continually evolve in response to changes in environmental regulations, waste oil composition, and engine requirements, those pilot scale processes which are likely to be fielded in the next few years will also be discussed. At the end of this section, the impact of conventional and recycle process technology will be discussed.

3.1 CONVENTIONAL BASE OIL PRODUCTION PROCESSES

In a typical process, lubricating base oil is produced from crude oil in a refinery by the series of processes shown in Fig. 3.1. First, the crude oil is separated by atmospheric distillation. This is followed by vacuum distillation into light/heavy and asphalt streams. Cuts selected for lubricating oil production are typically solvent extracted, using methylpyrrolidone as the solvent of choice, to remove undesirable aromatics. The raffinate stream containing lubricating oil is then treated with hydrogen (hydrotreated) to remove unstable compounds. After hydrotreating, the oil is dewaxed by additional solvent extraction or hydrocracking. Only a small fraction, perhaps 2%, of conventional crude oil contains the types of materials needed in a base oil from which lubricants can be made.

The manufacturing process is energy intensive and consumes 1.5 million Btu per barrel of finished base oil lubricant (Energetics 2007). This energy cost, which reflects a combination

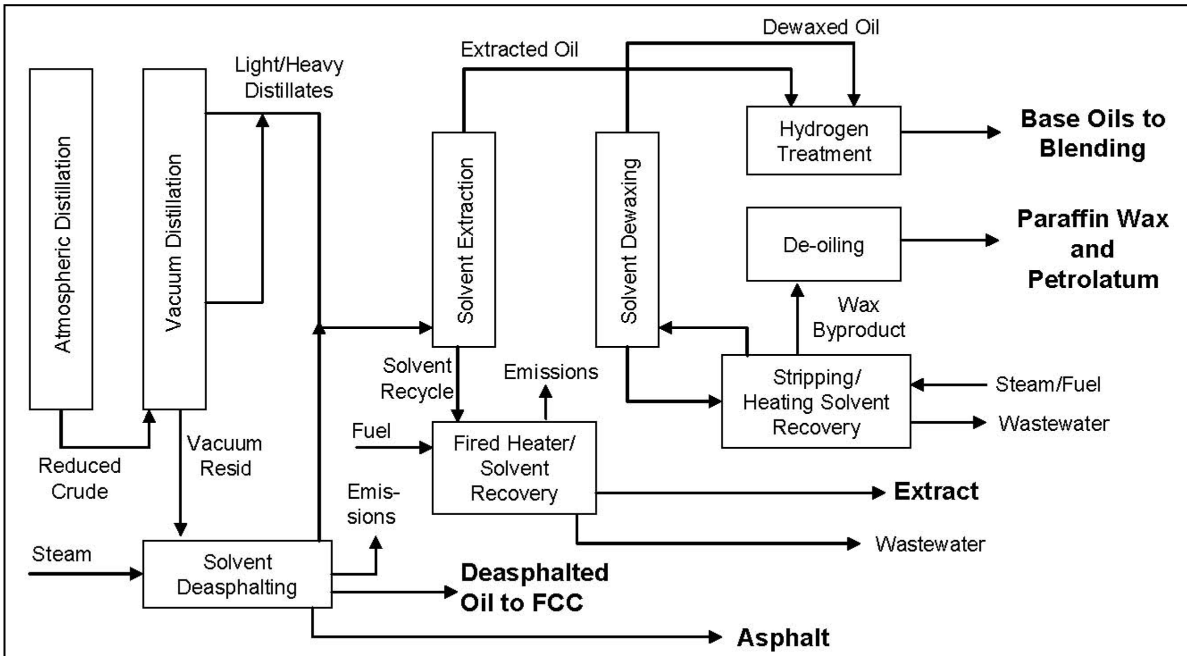

Fig. 3.1. Typical refinery process arrangement for producing lubricating oil. Source: Energetics 2007.

of process energy and hydrogen, is equivalent to nearly one-fourth of the energy in a barrel of crude oil for each barrel of base lubricating oil.

After refining, product base oils are then blended with additive packages to produce the desired lubricating oil properties. As discussed in Section 2, a number of different grades of conventional lubricating oil are currently marketed. Each grade requires a different base oil (or base oil blend) and an additive package specially formulated for its target use.

3.2 ADDITIVES USED IN CONVENTIONAL, RECYCLED, AND RE-REFINED OILS

Lubricant additives are typically prepared as proprietary packages which, when blended with a given base oil, provide desired properties under specified conditions. A detailed listing of more common additives is available from the Office of Fossil Energy report (2006, Table 9). However, major classes of multifunction additives include: 1) zinc dithiophosphates – antiwear, anticorrosion, antioxidant; 2) phenolate salts including alkali metal phenolates – detergent, anticorrosion; 3) long chain olefin, methacrylate, di-ene, and alkylated styrene polymer – viscosity modifiers; and 4) silicone polymers – antifoam. Other additives are used to provide metal deactivation, seal swell control, and decrease friction.

Additives, which may comprise 12-15% of lubricating oil, are typically separated from lube base oils during recycling and re-refining. Additives remain sequestered within, and likely not leachable from, most of the asphalt products produced by modern re-refining processes. However, combustion of additives in some industrial processes, such as cement manufacture, requires the use of air pollution control.

Cost effective additive recycle would be desirable from environmental, closed-loop, and economic perspectives. However, at present, even advanced re-refining processes are not reported to provide recycle of the additives used in preparing lubricating oil blends

3.3 HISTORICAL PERSPECTIVE ON WASTE OIL RECOVERY AND RE-REFINING

Technologies for reusing, recycling, and re-refining used lubricating oil to produce base oils have been developed and used over the past fifty years. In this time, lubricating oils have evolved to meet demands for higher temperature engine operation, extended lubricant stability, reduced wear, and a variety of environmental requirements. To meet these challenges, increasing amounts of additives and synthetic oils are routinely used to reduce wear, corrosion, foaming, and the pour point, and increase the viscosity index. These materials, together with increasing performance requirements, have led to the development of increasingly complex used oil recovery and re-refining processes.

In addition to the increasing variety of materials going into a lubricating oil blend, waste oil contains a variety of contaminants introduced or produced by the combustion process (water, oil degradation products) and from the engine itself (metal and metal oxide particles) and contaminants commonly introduced during oil change and collection operations, such as antifreeze or windshield washing fluid. Contaminants also include the additive package, which can constitute up to 15% of blended lubricating oils. A given lot of waste oil may also contain a variety of different grades and types of lubricating oils. The patchwork of federal, state, and local laws, taxes, grants, and loans, which govern the types of materials which may be batched, transported, and sold as used oil, also affect cost, composition, and quality of used oils in many ways.

Recovering or refining used oil requires removal of unwanted contaminants and modification and separation of the resulting oil mixture to produce marketable streams. Thus, the process technology for oil recovery and re-refining can be viewed as a simplified virgin oil refining process train that has changed, with time, to satisfy: 1) more demanding requirements for lubricating oil; 2) changing composition, cost and availability of used oil; 3) increasing environmental requirements; and 4) evolving laws. In general, the recovery methods have become more complex as product and industrial constraints have become more severe.

3.4 UNIT PROCESSES AND OPERATIONS

Across the last fifty years, a number of processes for successfully removing contaminants from used oil have been demonstrated. The most common of these are described below. Used oil processing methods range from those developed to merely recover the oils for reuse (for example, removal of water and metallic contaminants) to complex processing schemes which re-refine used oil to base-oil blending stock and a range of other products. A number of these processes have been operated at industrial scale, developed through pilot scale, or simply patented. Most successful process trains are rearrangements of a few unit processes used in conventional petroleum refining or other large scale industrial processes.

The bulk of water, solid particulates, and light hydrocarbons are removed from waste lubricating oil by pretreatment. For the remaining material to be recycled as base oils, several other classes of materials need to be removed. These include polar compounds, residual additives (which may include sulfur compounds and long chain polymers), and any remaining water and particulates.

3.4.1 Preprocess Treatment

Settling or filtration with or without additives is used as a pretreatment step in almost all oil recovery processes. This step removes some water and insoluble foreign matter (for example, metal and metal oxide particles) that interfere with later process steps. A dehydration or pre-flash distillation usually follows to remove water and light hydrocarbons.

Reverse osmosis or membrane filtration is also used as a recycling process by some organizations with transportation fleets. The authors' organization has treated used oil by membrane filtration (to remove water and particulates), replaced part of the normal additive package, and re-used the lubricating oil. This practice has also been reported for military vehicle and truck transport fleets. This practice may be decreasing with increased availability of recycled and re-refined oil or with the need to meet federal mandates for use of certified recycled products.

3.4.2 Sulfuric Acid Followed by Clay Sorption

Physical-chemical treatment with sulfuric acid and clay is widely known to be very effective in refining oil. It was widely used as an oil recovery step to remove polar compounds, residual additives, and suspended solids, in many early process trains. The sulfuric acid reaction was typically carried out at 30 to 40 ºC to avoid sulfonation or other changes to the oil. Clay was then added to absorb the residual acid. The amount of acid and clay required varied depending on the other process steps employed. A thermal heating step was used to both facilitate destabilization of the remaining additives and minimize acid and clay requirements.

The sulfuric acid – clay process produces a large amount of sludge that can contain up to 15% sulfur. Incorporation of large amounts of additives into lubricating oils decreased the effectiveness of sulfuric acid treatment and required significantly larger amounts of both acid and clay. Conditions were chosen so as not to deleteriously crack the oil. Because of environmental constraints, the use of sulfuric acid is now practiced only in less developed countries and for specialized streams in oil refining. Clay continues to be employed in some finishing processes, but disposal may be difficult.

Bleaching clay may also be used as a finishing treatment, although disposal may be difficult with current environmental regulations.

3.4.3 Thermal Treatment

Heating the oil to 250 to 400ºC to destabilize the additives in the waste oil is included in several processes. To minimize both precipitation of suspended material and degradation of the oil itself, the severity of thermal treatment is usually limited.

Bench scale laboratory tests are routinely performed parametrically to determine the optimum conditions for a particular waste oil. Maintenance of oil viscosity is typically a major concern. Thermal treatment applied to the sulfuric acid clay process could reduce the amount of acid by half. Sulfuric acid reduction is a significant process advantage because current composition standards mandate low sulfur contents for diesel fuel, a re-refining byproduct. Environmental protection standards also require reductions in sulfur oxide emissions in many regions.

3.4.4 Settling (Flocculation)

Simple settling and decantation are among the least expensive unit operations to remove water and solid materials from waste oil. The smaller the particles, the longer the settling time required. Physical-chemical treatment with additives to flocculate the smaller particles and react with metal contaminates are often included in the overall process. Water, sediments and sludges are removed by gravity methods or the process is followed by filtration or centrifugation.

3.4.5 Distillation

Multistage fractionation under pressure or below atmospheric conditions as practiced in the petroleum refining industry is the workhorse unit operation to separate the recovered oil into marketable products. Flash distillation is used as single step or a series of flash steps to remove low boiling fractions of water, engine fuel, and light hydrocarbons in most recovery processes. Distillation is the preferred method of solvent recovery where feasible. Where viscous liquids are evaporated, either a falling-film (typically gravity flow inside vertical tubes) or mechanically wiped-film evaporator is employed. Both of these methods allow vacuum operation under very low pressure (100 to 1000 Pa). Distillation and evaporation are widely used in almost all of the oil recovery processes as well as in the refining process.

3.4.6 Solvent Extraction

Oil is mixed with propane or other light hydrocarbon and phase separated. The light phase includes most of the oil and solvent and the heavy phase is mostly heavy residues. The propane is recovered from the oil by distillation and from the asphalt, etc. by thin-film evaporation. The recovered solvent is recycled to the process. A polar solvent mixture such as hexane/alcohol which precipitates suspended matter has also been used. In a few processes, methyl pyrrolidone is used as a solvent to separate aromatic hydrocarbons and heteroorganics.

3.4.7 Centrifugation

Continuous centrifugation has been applied in several oil recovery processes. Several companies responsible for the oil recovery process development have had skills in high temperature centrifugation.

3.4.8 Ultrafiltration

Hyperfiltration, also called ultrafiltration, has been used in a number of processes. Both inorganic and polymeric membranes have been utilized. The oil sometimes has been filtered while diluted with hexane or supercritical CO_2 to reduce viscosity. Generally, high tangential velocity is maintained to reduce membrane foaling. Pumping requirements may be high.

3.4.9 Catalytic Hydrotreatment or Hydrofinishing

Treatment with hydrogen and a catalyst under pressure to remove unwanted aromatics, heteroorganics, and olefins is a standard refining step and is incorporated in several oil recovery processes. Since many unwanted metals remain with the catalyst as sulfides, guard reactors are provided to protect the catalyst bed. If Group II or Group III base oils are to be produced, hydrotreatment is the best route.

3.5 COMPARISON OF RE-REFINING PROCESS ARRANGEMENTS

The unit operations and processes discussed above have been adapted from processes used extensively in the petroleum industry for use in waste oil recycle and re-refining. Significant improvements have been made across the fifty years in which waste oil processing technologies have been fielded. However, waste oil processing is essentially a recycling technology which must both adapt to continual changes in feedstock, product economics, and, most importantly, the environmental requirements discussed in Section 3. Continual changes in oil composition and in the market for different types of base oils also force technological change on this field. Tables 3.1 through 3.3 present summaries of groups of selected waste oil recycling and re-refining technologies which were fielded at industrial scale, while Table 3.4 covers advanced technologies which have been evaluated at pilot or smaller scale.

The processes summarized in Table 3.1 were developed by companies that recovered waste oil by acid-clay treatment. The early Meinken process, as well as the improved versions that use acid treatment and clay as their major contaminant removal step, are now regarded as obsolete in most developed countries. The disposal of the acidic sludge and the increased amount of additives in waste oil feedstocks, which made the process more difficult, were the major drivers for process evolution.

The major evolutionary process changes were developed to reduce the amount of acid required to treat oil additives, polar compounds, and residual suspended solids. The first types unit processes used were physical separation processes, including early vacuum distillation, tangential flow film fractionation, and clay centrifugation. Other processes improved clay and particulate separations with additives. One, the Entra process, used alkaline, rather than acid compounds and a combination of increased process temperatures and low process temperatures to decrease reaction time. The Entra process also broke the process into three sequential steps.

Table 3.1. Pioneering used oil recovery processes based on acid-clay technologies[a]

Process	Description	Remarks
Ecohuile	This is a process that eliminated the use of sulfuric acid and clay treatment from the Matthys-Garap vacuum distillation process. The simplified process increased oil yield and reduced environmental impact. Also additives were used to promote separation in settling. A pre-flash distillation eliminated the centrifugation step	Clay treatment as a finishing step at the end of the process was stopped in 2001.
Entra (Tubular reactors)	The process (without sulfuric acid) uses a series of three direct-fired upflow tubular reactors under vacuum at about 500 Pa and 400 ºC with millisecond reaction times. Dehydrated oil is introduced into the first stage. A fraction of a percent of proprietary sodium (0.2-0.8%) compounds is added to the second stage, and 4.4% clay is added to the third stage. Separators are included between stages to remove asphalt and sludge. The product from the third stage is vacuum distilled in a series of towers followed by a final spray tower to separate the various oil and fuel cuts.	
Matthys-Garap	After settling and an atmospheric flash distillation step at 180 ºC to remove water and volatile organics, oil fractions are separated by vacuum distillation. The column bottoms are centrifuged to separate asphalt and metals. The recovered oil fractions are then given an acid clay treatment. Sludges are separated by centrifuging.	The process addressed the trend to increase the amounts of additives in lubricating oil. This trend was resulting in reduced oil recovery yields. This process required technology to centrifuge hot viscous liquids.
Meinken	This was once the standard treatment process. The oil is reacted at near ambient temperature with 8-10% sulfuric acid and settled. After decantation, 3.5% clay is added and heated with a thermal fluid to 270 ºC , then cooled to below 120 ºC, decanted and filtered. The addition of vacuum distillation followed by dehydration before acid treatment is used to reduce acid consumption and sludge formation .	This was the most globally implemented and extensively used process. The improved version was widely used, but use now is declining and it is considered obsolete because of waste disposal issues.
Revivoil	Dehydrated oil from a flash distillation is thermally deasphalted by vacuum distillation at 2 kPa which is followed by either clay treatment or hydrotreatment. Propane is used to strip the asphalt bottoms from the still.	
Sotulub	Additives are added prior to the first flash dehydration step. After a second diesel fuel removal flash, the oil is vacuum distilled. A thin-film evaporator is used to process the asphalt stream. Additives are added to the vacuum distilled oil before it is fractionated into the product oil streams.	Sotulub switched in the 1980's from acid-clay to this process. No finishing was required because of the effectiveness of vacuum distillation coupled with thin-film evaporation.
Vaxon	Tangential-flow film fractionation stages were developed to produce a side cut as well as the top and bottom streams. Three or four modules are concatenated in series to obtain the oil fractions needed. The products are breached with clay or possibly hydrotreated or solvent extracted to reduce the polycyclic aromatic concentration to required levels	Process was developed as an alternative to classic acid-clay processing. Tangential flow helped avoid coking. The series of fractionation stages allowed process flexibility.

[a]Summarized from Audibert 2006.

However, at high petroleum prices, sulfuric acid – clay based processes might be attractive from energy and financial perspectives in countries where environmental standards are less strict or where sulfuric acid is less expensive.

Second generation technologies profiled in Table 3.2 were developed based on modern conventional refinery and industrial separations processes. For example, the CEP (Mohawk), Kinetic Technology International (KTI), and Regelub processes rely heavily on the use of distillation. Solvent extraction using methyl pyrrolidone was developed for the Bechtel and MRD GmbH processes and has been used successfully in other processes including the Interline, Bartlesville Extraction, and Flocculation – Organic Polar Solvent Extraction processes. The improved CEP and Simplified Mohawk-Evergreen processes use thin-film evaporation. The Regelub process also uses tangential or ceramic membrane filtration.

Table 3.2. Used oil recovery processes using second generation technologies[a]

Process	Description	Remarks
KTI	Kinetic Technology International developed a high vacuum process using falling film evaporators followed by hydrotreatment. The oil from a pre-flash step is vacuum distilled at 2 kPa to separate a diesel cut. The bottoms are redistilled at 200 Pa in a thin-film evaporator. After settling at 180 ºC, the still tops are combined with the diesel cut from the first distillation step, hydrotreated and distilled again at 3 kPa to produce diesel oil, as well as light and heavy oils.	KTI replaced the acid-clay treatment with this process in the 1980's.
Bartlesville Extraction	Similar to KTI with the addition of solvent extraction with a mixed solvent of butyl and isopropyl alcohols with methyl ethyl ketone.	Good quality oil, but pilot scale operation
CEP (Mohawk)	After pretreatment with additives, a flash stage removes water and gasoline. A second flash stage removes diesel fuel. This is followed by vacuum distillation. The bottoms from the vacuum distillation are redistilled in a thin-film evaporator to separate the asphalt. The vacuum still tops are hydrotreated as a whole and fractionated again to produce diesel oil, as well as cuts of light, medium, and heavy oils	Chemical Engineering Partners and Mohawk Oil Company successfully developed process technology to address the issues of fouling, corrosion and short catalyst life resulting from oil additives
Flocculation – Organic Polar Solvent Extraction	After a flash step to eliminate water and light hydrocarbons, the oil is contacted with a solvent to precipitate suspended materials. After settling, the solvent is recovered from the oil by distillation at 175 ºC. The recovered oil is finished by vacuum distillation, hydrotreatment or clay bleaching.	
Interline	Waste oil is pretreated with caustic and additives at moderate temperature. Then the oil is cooled and introduced with liquid propane cocurrently to a extraction vessel. The propane-oil-water-residue fractions are separated and the propane-oil fraction is heated and flashed to recover the propane. The residue fraction is stripped to produce asphalt. The oil from the flash tower stripped of water and solvent and fractionated into oil products by vacuum distillation.	
Mohawk-Evergreen	Catalyst poison elimination was added to recycle stream in the vacuum distillation steps	
Phillips Prop Technology	This is a two-step process for metal removal and hydrotreatment. In the first step aqueous diammonium phosphate and polyethoxyalkylamine along with flocculents are separately mixed with the oil and reacted in a series of continuous stirred reactors to form a slurry which is filtered to remove most of the metals in the oil. The oil is then hydrotreated using a Ni-Mo catalyst at 360 ºC and 750 psi. Excess hydrogen is washed and recycled.	Direct H_2 contact No preflash, vacuum distillation or separate deasphalting required
Regelub	Most of the water and sediment is removed by centrifugation at 80 ºC followed by two preflash stages. This is followed by hyperfiltration using tangential filters or ceramic membranes at 300 ºC. The product is then vacuum fractionated into product oils	Developed jointly by Matthys-Garap, CEA, and Total.
Simplified Mohawk-Evergreen	Diesel fuel recovery was moved upstream to the atmospheric flash step. An internal condenser was added to the thin-film evaporator to improve mass transfer.	This process was implemented by Evergreen Oil.

[a]Summarized from Audibert 2006.

Except for final finishing in the Flocculation – Organic Polar Solvent Extraction Process, clay was eliminated to address environmental concerns associated with the sulfuric acid-clay processes. In this process, clay may also represent a significant disposal cost.

The advanced waste-oil recovery processes profiled in Table 3.3 are configured to facilitate removal of 1) additives (Phillips Prop Technology), 2) polyaromatic compounds (MRD GmbH), chlorine (Probex-Proterra), 3) antifouling agents (Tiqsons Technology), and 4) asphaltic materials (UOP Hylub, MRD GmbH). This group of processes were also developed to produce marketable base oils and fuels, primarily by hydrotreating products. Most of them would be suitable for use in industrialized countries with strong environmental rules.

Table 3.3. Advanced used oil recovery processes using modern refining technologies[a]

Process	Description	Remarks
Bechtel	In the Bechtel process, waste oil is counter-current liquid extracted with 1-methyl-2-pyrrolidone. Solvent is steam stripped from extract stream and recycled.	Process developed by Bechtel. Process can be combined with other oil treatment processes.
MRD GmbH	Similar to Bechtel process, but optimized for removal of polyaromatic compounds and the preservation of synthetic oils and properties for re-refined products	Process developed by Phillips Petroleum.
Probex-Proterra	After pretreatment to remove water and low boiling materials, the oil is vacuum distilled. The distillates are solvent extracted with1-methyl-2-pyrrolidone at 40 to 65 ºC and the solvents recovered as described for Solvent Extraction above. Further steps of hydrotreating or clay bleaching could be used. Additionally a process to de-chlorinate and decrease its propensity to cause fouling by treating with a stream of non-oxidizing gas may be included as needed.	
Snomprogetti	After a standard preflash distillation, the oil is propane extracted. About 90% of the impurities are removed. The remaining oil is vacuum distilled and each cut is hydrotreated to produce the product oils	The second propane extraction allows hydrotreating tailored to each cut separately.
Tiqsons Technology	After pretreatment with additives to remove antifouling agents and a preflash distillation to remove water and light hydrocarbons, diesel oil is separated in a separate tower. This is followed by thin-film evaporation, hydrotreatment, and oil fractionation.	
UOP Hylub	Waste oil is filtered and mixed with hot hydrogen stream to 360 ºC at atmospheric pressure and flashed at 60 to 80 pressure atm depending on the feed to separate the asphalt. The hydrogen-oil stream is then passed through a guard reactor followed by the catalyst bed hydrotreating reactor, stripped of excess hydrogen and light fractions, and then vacuum fractionated into oil products	

[a]Summarized from Audibert 2006.

The requirements for waste-oil recovery processes, and for the oils produced by those processes, continue to evolve to address changes in waste oil composition, increasing environmental and engine requirements, and changes in environmentally-acceptable industrial plant operations. The pilot-scale processes in Table 3.4 include a number of current process technologies. Most of these processes use high temperatures.

The Krupp Supercritical process makes use of supercritical ethane extraction. Two processes employ high temperature molten metal (Recyclon-Degussa) and molten salt (Extramet) processes. Centrifugation and manipulation of microemulsion phases are used in the Codaten High Pressure process, while the Chuscen process uses a combination of ultrasonic mixing, manipulation of conventional liquid phases, and centrifugation. The Cermem Ultrafiltration process uses ultrafiltration with nanolayered alumina and silica, or alumina-zirconia nanocomposite, membranes on honeycomb supports. The Cermem process uses high recirculation velocities to decrease membrane fouling and deposit formation.

PetroTex Hydrocarbons, LLC., has completed pilot studies and intends to construct and operate its ReGen™ Process at industrial scale (23 million gallons per year). At present, it is difficult to determine which, if any, other pilot scale processes will be fielded at full scale.

Table 3.4. Used oil recovery process arrangements evaluated at pilot scale[a]

Process	Description	Remarks
Cermem Ultafiltration	Ultafiltration is carried out up to 0.3 MPa and 200 ºC using low-cost membrane supports similar to honeycomb ceramics used in catalytic converters. Membranes formed by applying layers of 500 Å alumina-zircon composite, 100 Å silica, 50 Å transition alumina, and 50 Å silica were tested. High recirculation velocities were used to slow membrane fouling and deposits.	Pilot plant study only Further research necessary
Chuscen (Ultrasound)	Waste oil is pretreated in a vacuum flash distillation to remove water and small hydrocarbons followed by ultrasonically mixing with white spirits for 15 minutes at 360 ºC. The solvent oil mix is settled, centrifuged at 7,000 g to remove insoluble material, and flash evaporated to recover the white spirits solvent for recycle. The small amount of white spirits remaining in the fuel keeps the flash point of the engine fuel within an acceptable range. The asphalt fraction can be used as such or further processed using the Extramet process. Insolubles were treated by electrochemical transformation.	Process produces fuel for turbodiesel power generation. Pilot operated at ~ 7 tons/day.
Codaten High Pressure	After removal of solids and water by centrifugation at 90 ºC, 5% water is added and the pressure is increased to 30-80 MPa at 60 ºC to form a microemulsion to transfer polar compounds into the aqueous microdropplets. The microemulsion is then destabilized by abruptly discharging it through a nozzle to atmospheric pressure at 200-500 m/sec. Chelating agents are added to complex the metals, and the stream residual water and solids are separated by centrifugation. The product oil can be processed to a base oil or a clean fuel.	Industrially funded research project in 1991. Financed by Chimirec in France.
Extramet	The oil is contacted with a molten alkaline carbonate and hydroxide salt bath at 300 to 450 ºC. Sulfides are removed from the salt bath periodically by air or steam oxidation. Residual carbon is removed as CO. The product oil is fractionated into product cuts.	Low bath temperature is needed to avoid cracking the oil. Small pilot scale. Technology needs further research
Krupp Supercritical	After atmospheric distillation to remove water and light hydrocarbons, the oil is extracted with supercritical ethane at about 10 MPa and 40ºC.	Pilot scale only.
PetroTex Hydrocarbons, LLC., Regen™	The ReGen™ process uses a series of flash distillation steps to separate water and light hydrocarbons, recyclable fuels, asphalt, and impure base-oil as separate streams. The base oil stream is solvent extracted with methylpyrolidone to produce a finished base-oil stream and an extract stream to be combined with the recyclable fuel stream for hydrotreatment and subsequent fractionation into Group II base oil and marketable fuels.	Pilot studies essentially complete. Company intends to construct facility.
Recyclon-Degussa	After settling and a dehydration and light hydrocarbon removal in a preflash, the oil is reacted with molten sodium at 200 ºC. After another flash distillation to remove light hydrocarbons, the oil is then fractionated into product oils by thin-film evaporation and fractionation. Light hydrocarbons are combusted for energy recovery.	Process was run at pilot plant scale but never was implemented in a large scale plant.

[a]Summarized from Audibert 2006.

3.6 COMMERCIAL USED OIL PROCESSES CLASSED BY THE DEPARTMENT OF ENERGY AS RE-REFINING WHICH DO NOT FALL WITHIN THE CURRENT ENVIRONMENTAL PROTECTION AGENCY RE-REFINING DEFINITION

Although a significant number of companies recycle used oil or waste transportation oil, most of the recycling processes convert the oil to a form, such as recycle fuel oil or marine distillate oil, in which it can be burned to meet industrial energy demand. In most of these processes, asphalt for roadways is a secondary product which can be used for safe disposal of most of the constituents of transportation lubricant additive packages. These uses do recover some of the energy and chemical content of lubricating oils but are once-through, rather than true "closed-loop" recycling processes.

In its 2006 report, the Department of Energy Office of Fossil Energy categorized several companies as used oil re-refining and processing facilities. Also, some of these companies recycle, clean, or purify industrial oils so as to permit their reuse. However, within the new Environmental Protection Agency Solid Waste Definition which took effect on December 29, 2008 the companies shown in Table 3.5 would now be classed as recyclers.

Table 3.5 Currently operating used oil recyclers previously classed by the Department of Energy as re-refiners[a]

Re-refiner / plant site	Base oil capacity, 10^6 gal/yr	Remarks
Consolidated Recycling, Troy, Indiana	12	Recycle of primarily synthetic industrial, rather than transportation, lube oils and antifreeze
General Oil, Detroit, Michigan	25	Recycle of industrial and transportation oils into industrial oils (downcycling)
Oil Re-Refining Company, Portland, Oregon (and a number of satellite sites)[b]	8.5	Recycle of base oils into commercial oils and cleaners. Overall product mix includes diesel fuel and asphalt.

[a]Source: Office of Fossil Energy 2006, updated from current corporate websites. The Office of Fossil Energy considered recycle of base oils to industrial lubricant use closed-loop, while the Environmental Protection Agency currently considers recycle closed-loop only if base oils are returned to their original use.
[b]Company has a number of collection and re-refining sites.

3.6.1 Consolidated Recycling

Consolidated Recycling is unusual in that it recycles glycol-based synthetic lube oils. It also provides antifreeze recycle. Consolidated Recycling operates a relatively small facility which uses conventional chemical process technology to provide closed-loop recycle of industrial process lubricants for industrial customers.

This process niche market is very different from the recycle of conventional petroleum-based transportation lubricants.

3.6.2 General Oil

General Oil treats a relatively wide range of oils. Each incoming batch must be segregated and separately assessed. As a part of this, a specific treatment is developed to optimize recovery of each different type of oil.

In the most general process, as listed on the company website, the oil is heated to around 200º F and treated with a combination of alkaline chemicals, polymers, and demulsifiers to separate and consolidate oil additives. The oil is then settled and decanted. If needed, further treatments are used to remove contaminants. Then the oil is dewatered in a drier and filtered through diatomaceous earth into a base stock holding tank. It is blended into a number of finished industrial products including cutting oils. This fulfills the Department of Energy requirements for closed-loop recycle because some industrial oils can be directly recycled, but it does not meet the current Environmental Protection Agency or proposed California requirements of recycle into the same product.

3.6.3 Oil Re-Refining Company

Oil Re-Refining Company is a recycler that offers transportation, holding, and, for appropriate streams, re-refining to base oil. The company services a large number of locations in Washington, Oregon, California, Nevada, Utah, Idaho, and Montana with a combination of locations in five states and cooperating haulers in other states.

This company appears to produce re-refined light and heavy diesel fuels, recycled fuel oil, and re-refined industrial oils. Since they re-refine industrial oils to make industrial oils, they are classified by Department of Energy as a re-refiner; however, they do not meet new Environmental Protection Agency or proposed California closed-loop oil re-refining standards.

3.7 COMMERCIAL USED OIL PROCESSES THAT MEET THE CURRENT ENVIRONMENTAL PROTECTION AGENCY DEFINITION OF RE-REFINING

As shown in Table 3.6, there are only a small number of true lubricating oil re-refiners in the U.S. These companies typically produce a range of products. The three that produce re-refined transportation oil generally produce asphalt and at least one grade each of fuel oil and lubricant base oil. As discussed below, the technologies used in these plants represent a pragmatic mixture of second generation and advanced oil-refinery processes. They also illustrate the extent to which the commercial success of re-refining is controlled by state laws, fees, and requirements. The companies profiled in Table 3.6 and described in more detail below meet both the Department of Energy and the current Environmental Protection Agency definition of re-refining because these processes return used transportation lubricants back into their original form.

3.7.1 Evergreen Oil, Inc.

The most successful and oldest U.S. oil re-refining facility is operated by Evergreen Oil, Inc. in Newark, California, As described by Audibel (2006) the process used by Evergreen has evolved from the first generation process developed by the Mohawk Oil Company, Ltd., of Vancouver. The first generation process used a chemical additive pretreatment to remove organometallic additives typical of waste transportation oils. This was beneficial because it decreased polymeric plugging and equipment corrosion.

The first generation process developed by Mohawk was licensed to Evergreen Oil and to a Canadian company, Breslube (acquired in 1987 by Safety-Kleen). Mohawk additionally licensed its pretreatment process to Chemical Engineering Partners, or CEP, in 1989 and significant information exchanges and cooperative agreements have existed between the companies across the intervening years. Among the collaborative areas have been processes to reduce compounds in waste oil which poison hydrotreating catalysts, lengthening hydrotreating catalyst life, and improvement of oil re-refining processes.

The steps involved in the original Mohawk Process, with approximate yields, are shown in Table 3.8. Essentially, the waste oil coming into the process is chemically pretreated to decrease corrosion and plugging caused by organometallic additives. After this, the oil is fed to an atmospheric pressure flash unit which removes water and gasoline. The dewatered, devolatilized oil is then fed to a flash unit operated under vacuum which removes diesel oil.

Table 3.6 Currently operating used oil re-refiners which meet the new Environmental Protection Agency definition of closed-loop recycle[a]

Re-refiner / plant site	Base oil capacity, 10^6 gal/yr	Remarks
Evergreen Oil, Inc., Newark, California	23.5	Recycle of primarily transportation oil feedstock
Heartland Petroleum / Lube Stop, Columbus, Ohio[b]	15	Recycle of primarily transportation oils to base oils blended into transportation oils, similar to Evergreen Oil Process
Safety-Kleen, East Chicago, Indiana[c]	70	Closed-loop industrial and transportation base oil recycle. Base oils are API approved.

[a]Sources: Office of Fossil Energy 2006, updated from current corporate websites, and Environmental Protection Agency 2008. The Office of Fossil Energy considered recycle of base oils to industrial lubricant use closed-loop, while the Environmental Protection Agency, in a ruling which took effect 12/29/2008 considers recycle closed-loop only if base oils are returned to their original use.
[b]Heartland projected operation during 2008.
[c]Current website data for East Chicago. Office of Fossil Energy used national total for oil. Collected at 110,000 sites and re-refined at several locations.

After this, the oil is fed to a vacuum distillation column coupled to a thin film evaporator. Asphalt is removed at the evaporator. The oil is then catalytically hydrotreated to produce a mixture of base oils containing a very small fraction of fuel gas and diesel oil. This stream is then fractionated to get desired cuts. The total yield of base oils from this process is approximately 65%, based on the total incoming waste oil stream.

Table 3.7. Original Mohawk Process steps[a]

Step	Additional feedstock	Separates	Yield, % of feedstock
Pretreatment	Proprietary chemicals		100
Atmostpheric pressure flash		Water Petrol	10 4
Vacuum flash		Diesel oil	6
Vacuum distillation + thin film evaporator		Asphalt	14
Catalytic hydrotreatment	Hydrogen		
Oil fractionation		Fuel gas Diesel oil Base oils	0.5 0.5 65

[a]Adapted from Audibert 2006.

By 1991, the first Mohawk process was operating in three plants, Evergreen in Newark, California; Safety-Kleen in Chicago, Illinois; and Mohawk in Vancouver, British Columbia with the resulting production of nearly 100,000 tons of base oil per year.

At present, the Evergreen Oil, Inc., Newark plant website indicates that a modified version of the original process is being used. The process steps consist of: 1) pretreatment, 2) water and light fraction removal, 3) fuel oil fraction removal, 4) separation of lube oil by distillation, 5) hydrotreatment to convert lube distillate to base stock, and 6) fractionation of base stock into desired cuts.

As reported in the recent Lawrence Livermore National Laboratory report (2008), the California Integrated Waste Management Board is interested in increasing the state's closed-loop, or full re-refining. They are considering increases in collection (including curbside), recycling fees, and "recycled content" marketing campaigns. The state is also considering mandating minimum recycled content for lubricating oil, a tiered monetary incentive structure that would provide a higher incentive for re-refining base oil than for asphalt; and decreasing the legal costs, time, and difficulties inherent in building new re-refining plant within California. (For example, Safety-Kleen expects to build its new facilities outside of California.) The state is also evaluating high comparative analytical costs, which encourage waste oil haulers to sell their oil out of state.

3.7.2 Heartland Petroleum / Lube Stop

Heartland Petroleum and Lube Stop, an oil-change chain, have collaborated to introduce an automotive lubricant change service which advertises, and charges a premium for, lubricants with 90% recycled base oils. In addition to the recycled base oils currently available on the market, Heartland and Lube Stop decided to develop a 15 million barrel per year plant dedicated to re-refining transportation lubricant base oils. The company broke ground on a facility using a process based on the Evergreen Oil / Chemical Engineering Partners process a year ago and announced that the facility would be operable in 2008.

Although this has been a difficult economic year, the collaboration has been very successful in marketing and in gaining recognition from awards.

3.7.3 Safety-Kleen

The process used by Safety-Kleen is based on the same technologies described above for the Evergreen Oil, Inc. Newark California plant. This technology was initially acquired by purchase of Breslube in 1987 by Safety-Kleen and has evolved to meet regulatory and market needs.

3.8 PROCESS IMPLICATIONS AND IMPACT

It is clear that transportation lubricating oil can be and, for the last forty years, has been recycled at industrial scale using a wide range of different process technologies. The technologies have evolved to match changes in environmental requirements, engine design, refinery process technology, and economic drivers. Older technologies have become obsolete or environmentally unacceptable, and new technologies have been developed and constructed. Some processes have been modified to improve performance or environmental acceptability. However, during operation, most of the industrial processes appear to have been profitable.

It appears that new U.S. drivers, as a part of both state and federal recycled-content requirements and the new Environmental Protection Agency solid waste definition, have the potential to greatly increase the amount and profitability of re-refining processes which produce directly re-usable lubricating base oils. This appears to be the case in California, and also, from its website, with the Defense Logistics Agency, which is the largest federal government purchaser. From the processes discussed above, it appears that only three suppliers, Evergreen Oil, Inc., Heartland Petroleum/Lube Stop partnership, and Safety-Kleen, meet the full requirements for closed-loop production of base oils directly reusable in transportation lubricants. Each of these operates regionally, due to the need to haul waste oil feedstock to a re-refining facility. This type of operation favors the development of new processes which meet current closed-loop process requirements and which serve as the re-refiner of waste oil for a given region.

4. FEASIBILITY OF THE PETROTEX HYDROCARBONS, LLC., REGEN™ PROCESS AND COMPARISON TO CURRENT INDUSTRIAL SCALE RE-REFINING PROCESSES

PetroTex Hydrocarbons, LLC., is seeking investors and partners for scale-up and full commercial demonstration of the ReGen™ oil re-refining process which it has developed. In a number of its programs, the Department of Energy uses a relatively standardized method for evaluation of the technical and economic feasibility of new industrial processes. Because the PetroTex Hydrocarbons, LLC., ReGen™ process is similar to the industrial scale processes used for lubricating base oil production in conventional petroleum refining operations, it will be compared to the criteria developed for the Industrial Technologies Program. In that program, a formal stage and gate system is used to ensure that technical, commercial, and market feasibility of a new technology have been evaluated prior to full commercial development. The lubricant market as a whole, as well as the historic development and the industrial scale deployment of earlier waste oil re-refining processes, were considered in previous sections. Technical and commercial feasibility, scalability, and competitive advantage of the ReGen™ process, relative to existing European and domestic processes, will be considered in this section. Because the price of crude oil has remained volatile for several years, the results of sensitivity analyses which profile the response of payout period to crude oil price will also be discussed. Regulatory issues and national energy impact will be considered in later sections of this report.

4.1 THE REGEN™ PROCESS HAS COMPLETED THE REQUIREMENTS FOR COMMERCIAL DEMONSTRATION

PetroTex Hydrocarbons, LLC., has completed the pilot plant and economic assessment studies that would be required in the concept development stage (Stage 3) of an industrial petroleum industry technology developed by the Department of Energy. These studies provide a basis for evaluating the commercial advantages and technical feasibility of the ReGen™ process technology (Gate 3) relative to other oil re-refining processes. Table 4.1 provides a summary of PetroTex Hydrocarbons, LLC.'s conceptual development and why it meets many of the formal Department of Energy requirements for commercial demonstration.

The ReGen™ process has been extensively evaluated at large pilot scale. Evaluations and model simulations have provided a reasonable basis for estimation of process energy and mass balances and have also shown that the process is likely to be technically feasible at larger scale. The oils have been evaluated by independent laboratories and found to meet requirements. Potential suppliers and haulers of transportation lubricants, such as rapid oil change facilities, have provided input to a plant for collecting waste lubricating oil as a feedstock, and a preliminary transportation profile has been developed. As a result of these studies, PetroTex Hydrocarbons, LLC., is evaluating scale-up and commercialization of the ReGen™ process at a site in Midlothian, Texas.

The PetroTex Hydrocarbons, LLC., has obtained a thirty acre site in RailPort, a 1,700 acre business park owned and operated by a cement and building materials supplier, Texas Industries, Inc. This facility is served by rail and has road access to Interstates 20, 35, and 45 and state highways 67, 287, and 360. Dallas, Fort Worth, and the Dallas-Fort Worth and Love Airports are less than 30 miles away from RailPort. This facility includes a Portland cement plant that is permitted to use waste-derived fuel. PetroTex Hydrocarbons, LLC., has also completed the processes required to secure permits to allow immediate construction and subsequent operation: 1) environmental and civil engineering studies, 2) obtained a special use permit from the City of Midlothian, and 3) received air emissions permits from the Texas Commission on Environmental Quality.

Table 4.1. PetroTex Hydrocarbons, LLC., has completed most evaluations needed for commercialization

Category	Tasks	Remarks
Technical feasibility	Constructed and operated a large pilot facility to evaluate a wide range of process feedstocks and operating conditions.	Pilot was large enough to prepare pre-commercial base oils for evaluation.
Scalability	Completed a detailed engineering analysis, including: 1) scale-up, 2) commercial facility design and costing, and 3) ability to meet Texas State's licensing and permitting requirements	Based on models and pilot tests, scale-up appears to be feasible. Proven unit operations are expected to reduce construction time, and installed spares, unscheduled down time. Quality and environmental issues have been evaluated and permits obtained.
Market and commercialization analyses	1) Selected a site for commercial development. 2) Evaluated waste oil market for that region. 3) Worked with regional suppliers of waste oil to develop a feedstock plan. 4) Developed a multisegment / multiproduct plan to ensure a stable market. (Important because the ReGen™ process produces base oils, asphalt, and diesel fuel from used oil.) 5) Performed oil price sensitivity analyses.	Re-refiners of transportation oils preferably purchase waste oil from collectors or from commercial entities, such as WalMart or Jiffy-Lube, which change oil and oil filters. This ensures a consistent supply and lowers potential contamination. A close working relationship may also lead to formulation and direct marketing of lubricating oil by the re-refiner. Markets for byproduct asphalt and diesel fuel also evaluated. Sensitivity analyses relative to crude oil price performed.
Comparison to other processes	PetroTex Hydrocarbons, LLC., is knowledgeable of the field, and a number of recent studies have provided information to assist this effort.	A recent reference book, *Waste Engine Oils: Re-refining and Energy Recovery*, provided a detailed basis for comparison with commercial processes (Audibert 2006). This is considered in detail in this section.
Can this process be deployed at many sites?	The initial commercialization scale was chosen because it is very close to the scale that would be needed in a number of other population-dense areas.	Other U.S. sites for similar oil recycling facilities include population-dense areas along of the eastern, Gulf, and western seaboards, Mississippi River, Great Lakes, and Hawaii.

As discussed in the previous section, transportation and, in a few cases industrial, lubricants, have been re-refined for more than forty years. The current domestic industrial scale re-refining processes were also profiled. This section discusses comparative economics for current domestic industrial scale lubricant re-refining processes and for an industrial-scale, 23 million gal per year, or 1500 barrel per day (BPD) ReGen™ process.

It is also important to note that the process can be deployed, at a comparable scale, in many population-dense areas. This includes most of the eastern, western, and Gulf seaboards and heavily developed areas along the Mississippi river and Great Lakes. Population-dense regions provide large amounts of waste oil while minimizing oil hauling distance.

4.2 DETAILS OF PETROTEX HYDROCARBONS, LLC., REGEN™ PROCESS

The ReGen™ process planned for the Midlothian 1,500 barrel per day plant is divided into three principal process sections: 1) a contaminant separation unit, 2) a molecular separation unit, and 3) a molecular treatment unit. The process is a novel combination of unit operations proven in refineries. The proposed plant site also includes transfer and tank storage facilities, process heat furnaces, and a cooling tower, offices, and laboratory support facilities.

The contaminant separation unit consists of four flash distillation stages in series. Use of a series of flash stages avoids the use of thin-film evaporation and allows fuel values to be optimally recovered. The first flash stage removes light hydrocarbons, water, and other polar compounds which are burned in the thermal fluid furnace for process heat. This amounts to about 3.3% (dry basis) of the input oil. Overhead product from the second and third flash stages is added to the molecular separation unit to recover fuel values. These streams are about 7.3% on a dry basis respectively of the plant input. The product of the fourth stage is the base oil stream and is feed to the molecular treatment unit. The bottoms from the fourth flash stage is withdrawn as asphalt flux to be marketed as Polyflux.™ This stream contains about 40.8 % of the input sulfur. These steps correspond to the distillation steps in the virgin oil manufacturing process. In this case the fuel and other contaminants, water, additive, and asphalt streams are removed.

The molecular separation unit is a liquid extraction system where the base oil product stream from the contaminant separation unit is separated into a marketable base oil product stream by solvent extraction. This produces a finished base-oil stream (50.1% of input) and a feed to the molecular treatment unit (22.8% of input) for further upgrading. The production of a marketable base-oil in this unit is regarded as a unique feature in the PetroTex Hydrocarbons, LLC., ReGen™ process. This base oil is classified as Group II or Group III oil and contains about 4.1% of the input sulfur. This unit corresponds to the solvent extraction unit process in the virgin oil refining unit. However, the energy and product loss associated with dewaxing and related products are eliminated because wax was removed when the oil was originally manufactured.

The molecular treatment unit is a catalytic hydrotreating system consisting of a series of hydrotreating towers, including catalyst guard towers. The feed is the combined fuel recovery streams from third and fourth stage flash distillation units and the extract from the solvent extraction section (22.8% of input). The product stream from the hydrotreating units (33.3% of input) is fed to an oil distillation fractionating system which separates Group I or Group II base oil (24.1% of input), diesel (7.3% of input) and naphtha fuel (1.3% of input) streams. The product streams contain, respectively, 0.6, 0.3, and 0% of input.

This section is very similar to catalytic hydrotreatment sections in the virgin oil manufacturing process. However, the energy intensity of the process is much lower than that of the virgin oil production process because much less severe treatment is needed because the base oils are recycled. It may also be termed hydrofinishing.

The energy requirements for the thermal fluid furnace and the molecular treatment unit heater total 18.4 million per hour or about 72 barrels of oil equivalent per day. This represents 4.4% of the thermal energy in the input stream; however, 3.3% of the input stream (up to 75% of the process energy requirement) will be obtained from the unrecyclable light hydrocarbons recovered from the first stage flash unit. Thus the used oil can be fully refined for about 1 to 2% of the combustion energy in the used oil feed (dry basis). This is an order of magnitude less than the 25% of petroleum energy expended to refine crude oil to lubricating oil (1.506 million Btu/barrel lubricant base oil total, see Energetics 2007).

The estimated installed cost of the nominal 1,500 barrel/day (1,650 barrel/day on a dry basis that the plant is in operation) Midlothian facility is $50.8 million dollars as presented in Table 4.2. As outlined in the PetroTex Hydrocarbons, LLC., Business Plan (May 2008), each shift is expected to have 3 plant operators plus a foreman or head operator per shift. Maintenance and other support personnel have been included in the operating costs presented in the economic comparison of waste oil treatment processes in Table 4.3.

Table 4.2 Estimated cost of PetroTex Hydrocarbons, LLC., 1,500 barrel per day ReGen™ facility in Midlothian

Item	Cost, thousand dollars
Equipment, installed cost	22,915
Site costs	11,265
Indirect costs	13,668
Startup and spares	2,936
Total cost of installation	50,784

Although these processes were installed under a variety of conditions in several countries, economics were updated to provide consistent estimates in U.S. dollars (Audibert 2006). An estimate for the PetroTex Hydrocarbons, LLC., ReGen™ process was prepared using Audibert's method so that it could be compared to other processes for waste oil re-refining.

Table 4.3. Comparative capacities, costs, and profit for ReGen™ and other processes[a]

Process	Capacity, tonne/year	Capital cost, 10^3 $	Profit	Depreciation	ROI, %	Pay-out, years
Revivoil[b]	80,000	35,635	26,091	3,563	73	1.2
CEP-Evergreen[b]	40,000	21,916	7,722	2,192	35	2.2
Sotulub[b]	20,000	18,400	9,600	1,800	52	1.6
UOP Hylub[b]	40,000	27,000	19,531	2,700	72	1.8
Interline[b]	27,000	12,600	7,044	1,260	68	1.5
Modern Plant Study[b]	80,000	49,951	22,309	4,995	44	1.8
PetroTex Midlothian Plant	80,000	50,800	57,355	5,080	123	0.8

[a]Capital cost is as redeemable capital. Profit is after depreciation and before taxes. Cashflow is profit + depreciation. ROI is profit / redeemable capitol expressed as a percent. Payout time is redeemable capital / cash flow in years.
[b]The Typical Plant Study by Audibert (2006) is based on a economic analysis of a "complete" re-refining plant conducted in 2005 which included a complete regeneration process and propane extraction asphalting unit.

The estimates shown in Table 4.3 include maintenance and other support personnel. The capital costs include offices, parking lots, and other site-specific items. However, capital cost does not include contingencies, reserves, and certain financing-specific costs. The major point that should be noted is that industrial scale processes for re-refining used transportation oils are successful and, in most cases, very profitable. The payback periods are typically very short, with the least-profitable CEP-Evergreen Oil process having a pay-out period of 2.2 years.

The PetroTex return on investiment (ROI) is the highest and the payout time is the shortest for the processes based on the analysis conducted by Audibert (2006). PetroTex Hydrocarbons, LLC., performed sensitivity analyses to evaluate the impact of crude oil price on payout time for their proposed facility. As shown in Figure 4.1, the PetroTex Hydrocarbons, LLC., process is estimated to provide a payout time of two years or less if oil remains at or above $50 per barrel. The break even point is approximately $21 per barrel of crude oil.

4.3 THE PETROTEX HYDROCARBONS, LLC., REGEN™ PROCESS IS LIKELY TO BE SUCCESSFUL

The PetroTex Hydrocarbons, LLC., ReGen™ process uses a combination of unit operations proven at industrial scale in both oil re-refining and proven petroleum refinery unit operations. This has led to development of a flexible process train which can be modified to treat a range of feedstocks and has many features that, with well-controlled operation, could provide a process advantage. The flash and conventional distillation operations follow standard oil refining and re-refining practice. Closely related technologies have been successfully used by Evergreen Oil, Inc. and Heartland Petroleum. These systems are expected to be successful at removing water and low-boiling materials, such as diesel fuel, from the base oil recycle stream. The last distillation stage is based on the proven technology used in refinery vacuum distillation column. A closely related system has been implemented by the Oil Re-Refining Company at a Los Angeles site. This process is expected to both produce unique products and improve the operation of downstream processes.

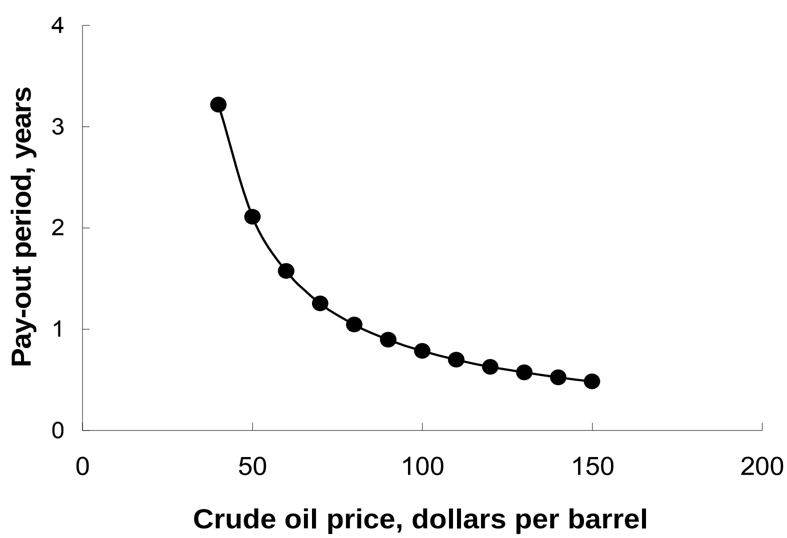

Fig. 4.1. Sensitivity of pay-out periods for PetroTex ReGen process to crude oil price. Source: PetroTex, LLC economic models and basis for projects 2008.

The molecular separation unit is a solvent extraction process based on both conventional petroleum refinery processes and processes successfully used in oil re-refining. Solvent extraction has been successfully used for decades as a part of the conventional petroleum refinery process for lubricant base oil production. The PetroTex process has been optimized to provide effective treatment of flash and vacuum distilled used oil feed.

The molecular treatment unit performs catalytic hydrofinishing. This unit process is a less-severe form of the catalytic hydrotreatment and has been successfully used in petroleum refineries. Catalytic hydrofinishing has also been used by oil re-refiners for over two decades. Although the PetroTex molecular treatment unit is based on refinery and re-refinery processes, the process treats less oil because of effective preprocess separations. It is also less severe than refinery processes because the used oil stream is hydrotreated during virgin oil refining.

On an environmental and operational basis, PetroTex Hydrocarbons, LLC., has also completed most of the legal, property, and environmental requirements necessary to start construction of their facility and operate their process. This is significant because other oil re-refiners, such as Evergreen Oil, Inc., have been unable to obtain the permits needed to increase capacity of their re-refineries in a timely fashion.

The sections below detail some of the technology improvements, including optimization of products and byproducts, intellectual property, and emissions minimization inherent in the PetroTex Hydrocarbons ReGen™ process.

4.3.1 Technology Evolution Inherent in ReGen™ Process

The major change in this technology is the development of patented methods that co-optimize high recoveries of Groups I and II base oils and also produce low-sulfur byproducts. These are expected to be critical factors in maintaining profitability because most competing processes have a tradeoff in base oil quality and yield.

PetroTex's ReGen process also meets a number of relatively new environmental requirements, including low sulfur content of diesel fuels. PetroTex's byproducts contain relatively low amounts of sulfur (≤0.003%), while those of other re-refiners contain > 0.5%.

Flexibility and the ability to adjust product mix to meet changing requirements is also important in commercial viability. Discussions with PetroTex staff also indicate that, in addition to Group I and Group II base oils, the system is able to produce Group III base oils. The system is also flexible in that it can adjust product mix and can also treat the major type of synthetic oils, polyalphaolefins. This is critical to meeting current market needs because higher performance and newer automobiles require lubricating oils blended from synthetic and Group II base oils.

Additionally, the recovery process has been adjusted to produce the lowest possible fraction of the lowest valued product, asphalt.

4.3.2 Likely Value of Intellectual Property

As discussed in the previous section, used oil re-refining is an area where technology evolution is recognized, licensed, and used. The reason is that, in most cases, used oil re-refiners serve an area limited by transportation costs and feedstock purchase contracts.

These businesses do not compete for feedstock because there are seldom two re-refiners in the same area. They seldom compete for purchasers because, again, transportation is a major cost and re-refining has, and likely will, remain only a part of the base oil market.

However, the three major re-refiners of used transportation oil appear to have licensed, and in some cases, cross-licensed, and fielded technologies which were developed by other re-refiners. The ability to produce base oils required by newer automobiles and, additionally, to process the dominant class of synthetic base oils, could be valuable to other re-refiners.

4.3.3 Minimization of Emissions and Waste Chemicals

PetroTex Hydrocarbons, LLC., has also developed the ReGen™ process to minimize air emissions. Light petroleum fractions removed in flash and distillation operations are used to fire the thermal fluid furnace unit. This makes maximum use of the fuel value in these gases and, at the same time, minimizes emissions.

Additionally, PetroTex Hydrocarbons, LLC., expects to recover and sell major waste chemicals produced by the process, sodium hydroxide / sodium sulfide, to pulp mills for use in chemical makeup. Hydrofinishing catalysts will be regenerated and recycled by the original manufacturer. Vapors from material transfer operations will be thermally oxidized.

The facility has been designed to make it possible to decrease greenhouse gas emissions. For example, a wet scrubber can be used to remove some of the greenhouse gases from the process furnace emissions.

PetroTex has also designed secondary containment in order to minimize the chance of a significant environmental spill.

4.4 CONSTRUCTION AND OPERATION OF THE PETROTEX HYDROCARBONS MIDLOTHIAN PLANT CREATES MORE THAN A THOUSAND JOBS

Working for the Renewable Fuels Association, John Urbanchuk (2008) evaluated the creation of jobs during construction of renewable fuels processing plants. The proposed PetroTex Midlothian plant is similar in size and traffic to a conventional renewable fuels plant. Additionally, both types of facilities have feedstock delivery by truck, distillation and chemical process equipment, a number of tanks, and large concrete working areas. It is likely that the construction labor relative to cost will be similar for both types of plants.

Using Urbanchuk's estimate of 27.5 jobs per million dollars of construction, the PetroTex Midlothian plant is expected to create approximately <u>1400 direct construction jobs</u>.

It is expected that the plant will operate for at least a decade. For each decade, it is expected that the plant itself will continuously employ 28 staff. <u>This will, across a decade, create jobs providing 280 person years of employment</u>.

The plant will process approximately 23 million gallons of dry used oil (or approximately 26 million gallons of collected oil) per year. Assuming that each driver collects approximately two loads per day (routes are likely to involve pickups from a number of businesses to minimize stored oil inventory), this is approximately 12 truck driving jobs, or <u>120 person years of employment for each decade the plant remains in operation</u>.

Re-refining will also create a number of ancillary jobs collecting used oil and shipping or hauling re-refined products to purchasers. These are harder to estimate without more detailed knowledge of the customer base.

4.5 PROCESS IMPLICATIONS AND IMPACT

The PetroTex Hydrocarbons, LLC., ReGen™ process is likely, even in the present volatile oil market, to have short pay-out periods, high rates of return, and state-acceptable operations. Since this technology is dependent on sufficient amounts of used transportation oil, available in many population-dense coastal, Mississippi, and Great Lakes metropolitan areas, it is likely that it could be used throughout these major areas of the U.S. Used oil re-refining processes could be used to serve the 70% of the U.S. population expected to live in these areas by 2020.

Although oil re-refining facilities are small, the impact of constructing these facilities on local employment is significant. If the plant size remains constant, each plant could create 1400 construction jobs and employ a permanent staff of 28. Additionally, transportation of used oil to the re-refinery will require approximately 12 truck drivers.

Assuming that transportation oil follows population, this implies a market cap of approximately two-thirds of the U.S. base oil market, or more than 30 million barrels per year, based on Energy Information Administration data. Of this, approximately 20 million barrels per year could potentially be collected and recycled.

It is likely that most used transportation oil re-refining processes will remain roughly the size of the PetroTex Hydrocarbons, LLC., Midlothian plant because of limitations in used oil collection and hauling. This implies that successful transportation oil re-refining process technologies, and plant process configurations, can be duplicated. A company with defensible intellectual property and trade-secret operating information could either build a number of such plants or could franchise or license the technology.

5. NATIONAL ENERGY, MARKET, AND CARBON DIOXIDE IMPACTS

This report evaluates the re-refining of used oils. Energy and mass balances for production of virgin lubricating oil base and re-refining of used transportation (or industrial) lubricants is complex. In evaluating the impact of lubricating oil re-refining, there are several major energy considerations: 1) the energy embodied in the lubricating oil itself; 2) the process energy required to produce virgin oil; 3) the amount or fraction of oil which can be recycled or re-refined; 4) volume or fraction of used oil which can be collected and re-re-refined; and 5) the comparative energy cost of virgin vs. re-refined oil. From a marketing perspective, it would be desirable to understand: 1) whether re-refined base oil can be used interchangeably with virgin oil, 2) whether consumers will accept products made from recycled oil; and 3) where used oil can most easily be collected and processed. It is also important to evaluate alternative uses for waste or used oils.

5.1 ENERGY BALANCES FOR LUBRICATING BASE OIL PRODUCTION AND RECYCLE

This section considers energy and mass balances for virgin and re-refined lubricating oils. The types of energy include embodied energy (lubricants are dense, high energy petroleum products) and processing energy. Base oils are used in both transportation and industrial lubricants. At present, recovery of the transportation oils is the most feasible.

5.1.1 Energy Embodied in Lubricants Used in the U.S.

As discussed earlier in Section 2, slightly more than 50 million barrels of lubricating base oil are consumed per year. Blended lubricants and greases used by the transportation and industrial sectors account for almost all of this material. As shown in Fig. 5.1, the energy content in U.S. lubricants has varied considerably since 1950. Between 1970 and the present, U.S. transportation and industry have consumed 300 to 400 Trillion Btus of lubricants per year. Present usage is roughly 300 Trillion Btu per year. In 2007, the transportation sector accounted for 145 Trillion Btu of lubricants, and industry, 154 Trillion Btu.

5.1.2 Virgin Base Oils for Lubricants Are One of the Most Energy Intensive Refinery Products

Energetics, Incorporated prepared a recent (2007) report evaluating the energy profile of the U.S. petroleum refining industry. Chapter 9 of this report provides a detailed breakdown of the energy required to produce lubricating oil from previously devolatilized feeds, such as distillates and condensates. As shown earlier in Figure 3.1, production of base oils for use in lubricants involves distillation, solvent extraction and requires a number of energy inputs: steam, electricity, fuel, and solvent make-up,. The process produces lubricating oils, paraffin waxes, and greases. Emissions include sour water, wastewater, and solvent losses.

Table 5.1 provides an estimate of the energy used in 2005 to produce base oils for industrial and transportation lubricants. The overall energy required to produce these materials, in addition to the energy embodied in the base oil itself, is approximately 92 Trillion Btu per year. The most energy intensive processes are solvent extraction, dewaxing and recovery.

Lubricating base oil production is also responsible for the generation of a number of pollutants, including 4.8 million pounds of toluene. Currently, there are Environmental Protection Agency

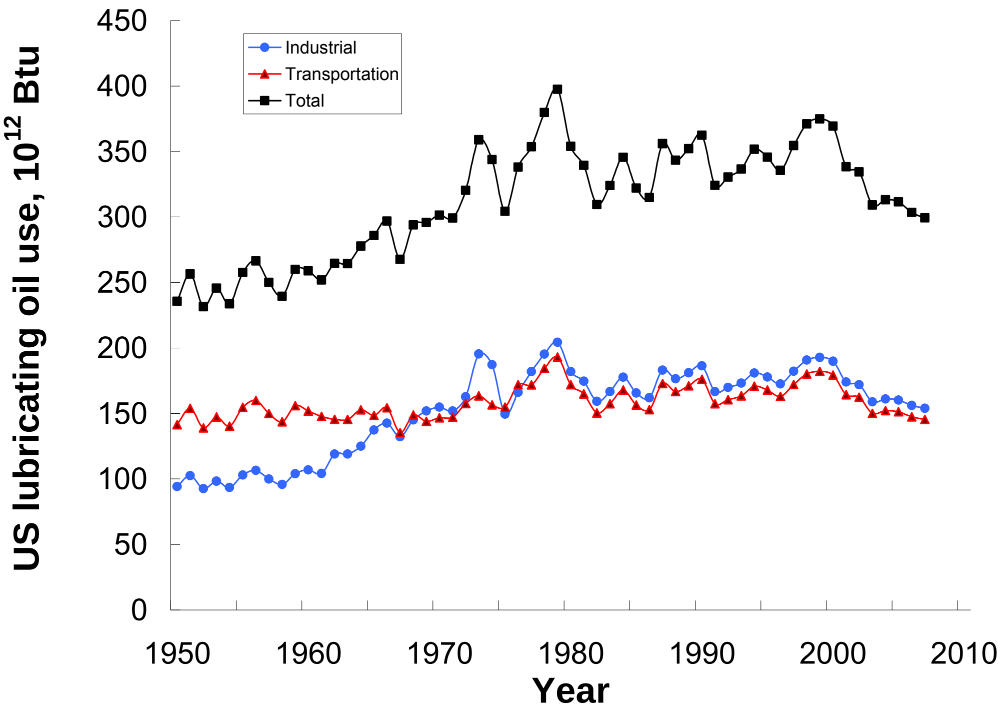

Fig. 5.1. Total annual energy content of lubricants used in U.S. industrial and transportation applications. Source: Energy Information Administration 2007.

best available technology limits of 0.257 lb phenolics, 0.297 lb total chromium, and 0.0248 lb hexavalent chromium per 1000 barrels of lubricating base oil. The bulk of these materials will be eliminated in re-refined oils.

5.1.3 Estimates of the Amount or Fraction of Lubricants which Can Be Collected for Recycle or Re-Refining

Office of Fossil Energy (2006) and Lawrence Livermore National Laboratory (2008) provided estimates of the fraction of used (primarily transportation) oil which was burned or lost during use in engines and oil which was or could be collected. Their estimates indicate that approximately 42% of lubricating oil is consumed or lost during engine operation. Forty percent of used oil is actually recovered, while 18% is disposed of improperly by dumping, landfilling, or improper use (for example, as a weed killer). These figures are relatively close to those from well-documented California data (40% consumed or lost, 43% collected, 17% unaccounted for). These are used, with the Energy Information Administration energy and volume data, to provide a basis for estimation of potential used oil feedstock.

From data available through the National Insurance Information Institute and the U.S. Census, it can be estimated that approximately 70% of U.S. citizens live in population-dense areas (cities, coastal / Great Lakes / Mississippi River) regions. Using Energy Information Administration data, the results for transportation lubricants on both energy and volume bases are presented in Table 5.2.

Table 5.1. Estimated 2005 energy requirements for U.S. base oil manufacture[a]	
Energy source	**National Use, Trillion Btu per year**
Electricity[a]	3.7
Natural gas	22.1
Refinery gas	39.7
Coke	14.6
Oils	2.7
Other energy	1.6
Electricity losses in generation and transmission	7.8
Total process energy	92.2
[a]Adapted from Energetics 2007. Calculated based on 61.2 million barrels of base oil. [b]Loss incurred in generation and transmission shown separately.	

5.1.4 Estimates of the Energy Required to Re-Refine Used Oil

Table 5.2 presents the energy requirements for the PetroTex Hydrocarbons, LLC., Midlothian plant and the energy embodied in the re-refinery products. The plant is sized for 23 million gallons per year of incoming waste oil. To facilitate estimation of national energy recovery from this process, energy used and produced as products per million gallons of waste oil is also tabulated.

Table 5.2. Embodied and process energy in PetroTex Hydrocarbons, LLC., ReGen™ Process products		
Item	Proposed plant per year	Per million gallons used oil
Energy inputs, Btu		
Hydrogen	3.25E+10	1.41E+09
Thermal furnace (TIFF)	1.28E+11	5.58E+09
Feed heater	1.74E+10	7.58E+08
Light gas utilized in process*	-1.06E+11	-4.59E+09
Net input energy	7.26E+10	3.16E+09
Energy embodied in byproducts, Btu		
Diesel	2.67E+11	1.16E+10
Naphta	4.56E+10	1.98E+09
Asphalt	4.24E+11	1.84E+10
Net energy in byproducts	7.37E+11	3.20E+10
Energy embodied in base oil products, Btu		
Group 2	1.93E+12	8.40E+10
Group 1	9.30E+11	4.04E+10
Net energy in base oils	2.86E+12	1.24E+11
Energy embodied in all products and byproducts, Btu		
Total net product and byproduct energy	3.60E+12	1.56E+11
*Uses non-marketable gas stripped from feed.		

Table 5.2 indicate that re-refining lubricants uses less energy than does production from virgin petroleum in a conventional refinery process. Additionally, the process recovers much of the

energy contained in used oil as energy embodied in products. As shown in Table 5.3, the amounts of energy which can be recovered on a national basis are significant.

Table 5.3. Volume, energy content, and disposition of transportation lubricants

Stage	Volume, million gallons	Embodied energy, trillion Btu
Used in 2007	1008	145
Consumed or burned	423	61
Recovered	403	58
Uncollected	181	26
In population-dense area[a]	409	59

[a]Estimated based on fraction of population and on recovered and uncollected oil.

Based on these calculations, it appears that approximately 60 trillion Btu of used transportation oil are available from recovered oil or from a combination of uncollected and recovered oil currently estimated to be used in population-dense areas.

If the PetroTex Hydrocarbons, LLC., ReGen™ process were used to re-refine the approximately 400 million gallons of used transportation lubricant, the products and byproducts shown in Table 5.4 could be produced at the energy use shown.

Table 5.4. Energy embodied in products which could be produced from 400 million gallons of domestic used oil with PetroTex ReGen™ process

Item	Energy, trillion Btu
Inputs	
Hydrogen	0.565
Thermal furnace (TIFF)	2.23
Feed heater	0.303
Light gas utilized in process*	-1.84
Net input energy	1.26
Embodied in byproducts	
Diesel	4.65
Naphta	0.792
Asphalt	7.37
Net energy in byproducts	12.8
Embodied in base oil products	
Group 2	33.6
Group 1	16.2
Net energy in base oils	49.8
Embodied in all products and byproducts, net of process inputs	
Total net product and byproduct energy	62.6

*Uses non-marketable gas stripped from feed.

The energy embodied in the re-refined base oils and in the other products indicate that, implemented at industrial scale in U.S. population-dense areas, the PetroTex ReGen™ process has the potential for national energy savings as high as 60 Trillion Btu per year. This market impact is within the normal range for energy conserving industrial technologies.

Additional energy savings could be realized where oil is re-refined several times. Discussions with PetroTex Hydrocarbon staff indicate that approximately 75% of the total content of base oils can be obtained from re-refining used oil. Since it is possible to re-refine used oil several times – the base oils are not degraded in the process – energy savings could be higher. However, this will depend on market penetration and on diligent collection of used oil.

5.2 MARKET RESPONSE TO RE-REFINED LUBRICATING BASE OILS

Market response to the use of re-refined base oils in transportation lubricants is described below. First, it appears that re-refined base oils can be used interchangeably with base oils produced from virgin petroleum, provided that interchangeability is evaluated using the same test methods. Thus, there appears to be no barrier, from the American Petroleum Institute, ASTM International (formerly the American Society for Testing and Materials), or the Society of Automotive Engineers, to marketing of these materials, provided that their quality is assured and maintained. As discussed below, there is increasing consumer acceptance of recycled or “green” products, including re-refined base oils.

5.2.1 Re-refined Base Oil Can Be Used Interchangeably with Base Oil from Virgin Petroleum

Re-refined base oils have become standard products. For example, they are covered by the American Petroleum Institute’s Interchangeability Guidelines (2008, Appendix E). The major American Petroleum Institute requirements are that the re-refined base stock be free of contamination and that it pass the same quality evaluations used to evaluate interchangeability of base oils produced from virgin petroleum. These include evaluations for saturates (ASTM method D2007); viscosity index (ASTM method D2270); and sulfur (ASTM methods D1552, D2622, D3120, D4294, or D4927).

In addition to meeting the ASTM standards, Group I, II, or III base stocks must contain less than 90 percent saturates and/or greater than 0.03 percent sulfur and have a viscosity index greater than or equal to 80 and less than 120. In addition to physical properties and composition, some vehicle manufacturers may require engine tests to verify performance. The American Petroleum Institute also requires that, for interchangeability, standard Society for Automotive Engineers Viscosity-Grade engine tests be performed according to the methods described in Interchangeability Guidelines, Appendix F.

5.2.2 Consumer and Government Acceptance of Re-refined Content Lubricants

As they accept recycled content in reproduction and multiuse paper, consumers appear to be willing to accept re-refined content in motor oil. Lube Stop and Heartland Petroleum have effectively conducted a market test of this using a motor oil which is labeled and advertised to contain a 90% content of recycled base oil. Lube Stop is able to charge an additional $6 per oil change (approximately $1.20 per quart) for this product. This indicates that consumers both accept and actively seek transportation lubricants with a high recycled content.

The Defense Logistics Agency has also been providing oil products re-refined to its specifications by a contractor. These recycled products have met with good acceptance and the Defense Logistics Agency has developed a functional system for collecting and transporting used oil for re-refining. Additionally, their website indicates that they will assist other federal agencies in purchasing re-refined oil and that its performance is acceptable.

5.3 COMPARISON OF CARBON DIOXIDE PRODUCED IN REFINING AND RE-REFINING BASE OILS

Table 5.5 shows the production of the major greenhouse gas, carbon dioxide, in producing 400 million gallons of base oil from petroleum and in the same quantity of used oil (dry basis). Re-refining produces less than 22% as much carbon dioxide as the original refining process used to produce the oil.

Table 5.5 Carbon dioxide generated in production of 400 million gallons of base oil from crude oil and by re-refining 400 million gallons of used oil[a]

Process	CO_2, million tons per year
Conventional	1.040
ReGen™ re-refining	0.224

[a]Based on Energetics 2007.

5.4 ALTERNATIVE USES FOR USED LUBRICANTS

As shown in Table 5.6, there are a number of current uses for recycled or reprocessed waste transportation oils. These uses are classified, based on the system developed by Lawrence Livermore for the California Integrated Waste Management Board, into processes for closed-loop recycling (production of base oils for direct reuse in transportation lubricants), single use recycling (recovery of waste transportation oils as combustion feedstocks or road asphalt), and downcycling (recovery of performance degraded base oils for use in industrial lubricants or specialty fuels).

As described in detail by Lawrence Livermore National Laboratory, the State of California is considering methods for decreasing single use recycling of used oil and establishing requirements for closed-loop recycling. It is expected that this will be paired with efforts, such as increased fees and taxes, which encourage collection and re-refining of used oil.

Table 5.6. Alternative markets for used lubricating oils[a]

Use	Recycle type	Fraction of recycled oil
Asphalt flux	Single use	0.31
Re-refined	Closed-loop	0.18
Space heaters	Single use	0.12
Industrial boilers	Single use	0.10
Utility boilers	Single use	0.08
Steel mills	Single use	0.08
Cement kilns	Single use	0.03
Other	May include downcycling into other industrial oils	0.10

[a]Adapted from Office of Fossil Energy 2006.

5.5. ENERGY, MARKET, AND GREENHOUSE GAS IMPLICATIONS AND IMPACT

It appears that the use of PetroTex Hydrocarbons, LLC., ReGen™ process has the ability to recycle approximately 60% of total domestic transportation lubricant oils. Most of the material would be recycled as base oils which could be reformulated to produce transportation lubricant oils. This is a true closed-loop recycle process, within the new Environmental Protection Agency definition, which would have a corresponding impact on the energy used in the production of lubricants.

Most of the used oil is returned as true closed-loop recycled products. These meet proposed California requirements. Additionally, the ability to recycle these lubricant oils increases U.S. jobs for both processing and collecting. Closed-loop recycling, which has been successfully implemented for paper products, decreases the need to import oils.

Recycled transportation lubricants appear to have good consumer acceptance in the markets where they have been evaluated. Both the Defense Logistics Agency and the Lube Stop quick oil change centers have found that customers preferentially choose the recycled oil product.

In comparison to lubricants produced by refining of virgin petroleum, re-refining used oil reduces greenhouse gases by 78%. On a national basis, re-refining 400 million gallons of used transportation oil would prevent release of nearly 750,000 tons of CO_2 per year.

6. IMPACTS OF FEDERAL AND STATE REGULATIONS ON OIL RE-REFINING

Most re-refining processes are profitable. That is to say, they have short pay-out periods and high rates of return on capital as discussed in Section 4. However, federal, state, and, in rare cases, local regulations have a significant impact on the ability to re-refine used oil and the profitability in so doing. Some regulatory requirements are beneficial in terms of increasing used oil collection and recycling or re-refining, while others tend to make it more difficult or more expensive to implement recycling. There are significant numbers of federal and state regulations. Major types of state and local regulations are discussed in detail below.

6.1 FEDERAL REGULATION OF USED OIL

Federal regulations have historically been relatively straightforward. They include: 1) recommendations and requirements for use of "substantially equivalent" products (such as re-refined base oils) where they can be obtained at a comparable cost; 2) creation and promulgation of requirements and regulations for recycled content and performance of various materials; 3) determination of hazardous content of materials such as used oil; and 4) requirements for minimization of energy use and greenhouse gas generation. These requirements were significantly strengthened by recent executive orders and a typical executive order will be discussed in more detail.

6.1.1 Environmental Regulation

The 1986 decision (51 FR 49000) by the Environmental Protection Agency not to list recycled used oil as a hazardous waste under the Resource and Conservation Recovery Act is the most important single environmental regulation affecting collection and re-refining of used oil. The Environmental Protection Agency later issued corresponding guidelines for handling and recycling used oil (*Managing Used Motor Oil* 1994).

The Agency has continued to encourage used oil re-refining and recycling, primarily to minimize improper disposal of used oil, and has encouraged states to adopt the Used Oil Management Standards described in 40 CFR Part 279.

The Energy Policy Act of 2005, section 1838, required the Department of Energy, in conjunction with the Environmental Protection Agency, to evaluate the energy and environmental benefits of re-refining used lubricating oil and to determine what federal steps would increase the collection of used oil and its re-refining and conversion to other beneficial products. Recommended steps included information collection and exchange (practices, rural areas, and census of used oil combustion space heaters) as well as education. Additionally, initiatives to require oil retailers to accept used oil were recommended.

In addition to this, the Environmental Protection Agency in October, 2008, issued a rule to encourage beneficial recycling by reclamation (EPA530-F-08-006). This rule contains a provision to exempt materials that are generated and legitimately recycled or reclaimed from being classed as solid waste under the Resource Conservation and Reclamation Act.

Most U.S. used oil is burned or recycled as "downgraded" products. The 2008 Environmental Protection Agency ruling is particularly favorable to "closed-loop" recycling processes, including re-refining base oils to permit direct re-use in lubricants. The rule does not provide a corresponding exclusion for generated material which is expected to be burned for energy recovery. This rule is expected to encourage the development of used oil re-refining processes.

6.1.2 Regulation as a Recycled Product

The Environmental Protection Agency, through its Comprehensive Procurement Guidelines for Vehicular Products (2007), indicates that a product which contains 25% or more re-refined base oil qualifies as re-refined lubricating oil, hydraulic fluid, or gear oil. Under the current regulations, this material will be preferentially purchased by government agencies and their contractors.

Additionally, as described above, re-refined lubricating oil is treated as a recycled material, rather than as a solid, potentially hazardous, waste, under the new EPA530-F-08-006 definition of solid waste.

6.1.3 Used Oil Collection and Recycle by Federal Departments and Agencies

Federal agencies are required to purchase and, where possible, collect and recycle used transportation oils. The Defense Logistics Agency and the U.S. Postal Service both report collecting used oil for recycle by contractors on their websites.

6.1.3.1 Requirement to purchase re-refined transportation oils

Executive order 13423 (2007) requires that federal agencies purchase recycled products, including re-refined transportation oils.

6.1.3.2 Agencies and departments which collect and recycle used oil

The U.S. Postal Service and the Department of Defense, through the Defense Logistics Agency, collect used oil. The used oil is transported, re-refined, and recycled back to their federal vehicles by service contractors. Use of re-refined oil in military vehicles has been approved by the Society of Automotive Engineers. The U.S. Army Tank-Automotive and Armaments Command qualified the oils under a specification, MI-PRF-2104H (2004), for use in combat and tactical vehicles.

The Richmond, Virginia, Defense Supply Center offers for sale a number of classes of closed-loop re-refined motor oil. As shown in Table 6.1, these meet performance specifications comparable to those for lubricating oils produced from virgin petroleum.

As noted, both two classes of commercial motor oils are available from the Defense Logistics Agency for use by non-Department of Defense customers, including both contractors and other federal agencies. Department of Defense contractors which obtain a Department of Defense Activity Address Code may also purchase re-refined oil through the Department of Defense EMall; MILSTRIP or FESTRIP purchasing process; or by calling the Defense Logistics Agency Customer Interaction Center number, 1-877-DLA-CALL.

6.1.3.3 Estimates of federal government production of used oil

In 2006, the U.S. used 100 Quadrillion Btu of energy. The energy in 500 million barrels of crude petroleum, although it may vary with source, is typically about 1 Quadrillion Btu. Departments and agencies of the U.S. federal government have historically consumed fuel

Table 6.1. Available Defense Logistics Agency motor oils made from re-refined base oils			
Oil types	**API Service Classes**	**SAE Specification**	**Remarks**
Tactical mil spec motor oil, 10W, 30W, 40W, 15W-40	SJ, CF, CF2, CF4, CG, CG4		
Administrative commercial motor oil, 5W-30, 10W-30	SJ, GF2	J2362	Non-DoD customers
Heavy-duty diesel commercial motor oil, 30W,[a] 5W-40	CF, CF2, CG4	J2362	
Heavy-duty diesel commercial motor oil, 5W-40	SJ, CF, CF4, CG4, CH4		Non-DoD customers Additionally meets: MACK EOM Plus, Cummins Diesel 20076, US Post Office
[a]30W meets only CF, CF2			

comprising between 1 and 2% of total U.S. domestic energy usage, depending on Department of Defense needs. This can be roughly estimated at 500 million to 1 billion barrels of crude petroleum. Lubricants account for roughly 1% of the total federal use, or 5 to 10 million barrels per year.

The major federal fuel consumers are: 1) the Department of Defense (75%), 2) the U.S. Postal Service (5%), and 3) the Department of Energy (5%). Together, these account for 85% of total federal government fuel use. Most Postal Service and Department of Energy facilities operate within the continental United States, while Department of Defense operations are global. Although considerable variation in Department of Defense U.S. fuel use levels is expected, it is not unreasonable to expect that at least one-third of fuel usage (25% of federal) will be domestic. This brings the combined domestic total for these three entities to approximately one-third of federal use, with approximately 60% of this material recyclable. The three agencies could provide, at most, approximately 1 to 2 million barrels of used oil (neglecting water). Depending on losses and on fuel change rates (oil is typically changed in low-use vehicles at least twice a year, rather than every 5000 miles), this could provide feedstock for one to four oil re-refining facilities.

At present, there is some potential for deployment of smaller “package plants” to large military bases, and to bases where supply and transport are expensive, in either personnel or financial terms, or where the remoteness of the base makes resupply difficult.

6.1.4 Greenhouse Gas and Energy Footprints

The market for re-refined base oils, which would be used in “closed-loop” transportation lubricants, is benefitted by federal regulations that mandate the use of recycled content materials, decreased energy footprint, and low greenhouse gas emissions profiles. The federal government has a long history, discussed above, of mandating use of products meeting recycled content standards. Climate change, greenhouse gas emissions, and energy footprint (or energy intensity) regulations are more recent. These may change when the successor to the Kyoto Treaty is negotiated.

It is important to note that Presidents Bill Clinton and George W. Bush wrote executive orders with comparable intent. Clinton's executive orders did not establish specific greenhouse gas reduction metrics. Because of oil price spikes, Bush's executive order specifies metrics for energy and water use which, if met, would decrease federal government operating cost within a relatively short period. This most recent such order is used as an example of an executive order decreasing petroleum use and requiring recycling.

As shown in Table 6.2, Executive Order 13423, January 24, 2007 requires federal agencies and their contractors to reduce energy and water use in a number of different ways and, additionally, to increase use of recycled-content, biobased, energy-efficient, and other environmentally preferable products. Recycled product use is mandated as standard purchasing practice, but, unlike earlier orders and Environmental Protection Agency requirements, this executive order does not require that recycled products provide comparable performance or cost.

Agencies and government contractors that operate vehicle fleets are also required to increase use of non-petroleum based fuels by 10% per year and to implement strategies to reduce solid waste, minimize hazardous chemicals, prevent pollution, and increase recycling of post-consumer materials.

The impact of this executive order is that federal agencies will be required to purchase re-refined oil whenever it is available and, additionally, to collect used oil for transportation to a re-refiner. The Defense Logistics Agency and the U.S. Post Office are among the agencies actively working to increase the amount of their used oil which is collected, transported, re-refined, and reused.

Table 6.2. Energy and materials reductions required by Executive Order 13423

Item	Base year	2015 Reduction	Remarks
Energy intensity	2003	30%	Or 3% per year
Petroleum products used by fleets of vehicles	2003		Petroleum product use reduction, 2% per year coupled with 10% per year increase in use of non-petroleum fuels[a]
Water	2007	16%	Or 2% per year

[a]May not be achievable at DOE facilities which already have significant biobased fuel use.

The overall impact of these regulations on startup companies is unclear. Use of extended supplier contracts by large agencies, such as the Defense Logistics Agency, could advance the interests of a small group of established suppliers while effectively locking newly formed competitors out. On the other hand, mandates to use high recycled content multipurpose office papers have led to development of a large group of competitive suppliers.

6.2 CALIFORNIA AS AN EXAMPLE OF STATE REGULATION OF USED OIL

There is considerable variation in state and, where relevant, local regulations. Where regulation increases collection of used oil or provides funding to encourage development of used oil collection centers, this can be an advantage. Environmental regulations which require lengthy permitting or mandate expensive analyses are viewed by used oil transporters and re-refiners as costs or challenges. The State of California uses a wide variety of regulations, incentives, and taxes to regulate collection, transportation, and recycle of used oil. The California Integrated Waste Management Board, which is considering both improvements to the state program and methods for adjusting the state program to meet the new U.S. Environmental Protection Agency rules regarding Modification to the Definition of Solid Waste, recently contracted with Lawrence Livermore National Laboratory to provide independent assessment of the program and alternatives (2008).

6.2.1 Incentives, Fees, and Taxes

The major California State tax is $0.16 per gallon on oil produced from virgin crude oil. The same amount is rebated for each gallon collected by a center. This amounts to a maximum of $800 for each 5000 gallons (tank truck) collected. It is thought to contribute significantly to the operating revenue which supports collection centers.

6.2.2 Pre-Construction and Expansion Permitting

Evergreen Oil, the major re-refiner in California, indicated in a stakeholder review session that streamlined pre-construction and expansion permitting would be very welcome. This is supported by an evaluation of postings on the Evergreen Oil company website which indicate that permitting can add months or years to the time required to construct new facilities. For example, permitting for the current Evergreen Oil process expansion required seven years to complete. This is a significant barrier to oil re-refining and greatly increases the cost of building new facilities.

6.2.3 Use Permitting

California State requires that users who combust products made from used oil obtain permits. These permits are presently limited, and are issued primarily to “grandfathered” or “pre-existing” combustors of used oil. It is likely, that in light of new Environmental Protection Agency changes to the definition of solid waste, California State will limit or eliminate used oil combustion permits.

6.2.4 Environmental Regulation and Mandatory Chemical Analyses

As of summer, 2008, California State regulates used oil as a hazardous waste. As such, California State requires that used lubricating oil be analyzed for a number of materials, including polychlorinated biphenyls, flash point, total halogen content. The cost of performing these analyses imposes a cost as high as $0.50/gallon on re-refiners. This leads to lower in-state payments for used oil, which decreases the rate at which California used oil is reprocessed in-state. As a result, it may be attractive to re-refine used lubricating oil in adjacent states.

This may be changed in response to the U.S. Environmental Protection Agency ruling which classifies used oil destined for re-refining as other than a solid waste. If California chooses to accept this ruling, it would make re-refining within California more attractive.

6.2.5 Used Oil Re-refining in Comparison to Currently-Permitted Recycle

California State Integrated Waste Management Board currently permits several types of used oil recycling. These include closed-loop recycling (re-refining of used oil and reformulation of substantially equal lubricating oil using re-refined base oil), single-use recycling (formulation of products, such as oils for combustion, which can only be used once), and downcycling (formulation of products with quality below that of the original product).

When the Lawrence Livermore National Laboratory report was prepared, U.S. Environmental Protection Agency rule EPA503-F-08-006, which does not treat burning for energy recovery as an exclusion to the definition of solid waste, was out for comment but had not been released. This regulation is expected to focus the California State used transportation lubricant program toward production of base oils for recycle into transportation lubricants. The other two products typically produced from used transportation oils, recycled fuel oil and marine distillate fuel (or marine diesel oil) are burned as fuels. Burning as fuels will cause these materials to be treated as Resource Conservation and Recovery Act solid wastes, rather than as recycled materials excluded from solid waste requirements.

Additionally, both products are considered to be downcycled and single use. As such, they do not meet the California State definition of "highest and best use." It was noted that California State regulates, and has grandfathered, permits for used oil combustion in the forms of either recycled fuel oil or marine diesel oil. It was also recommended that California State take steps, including taxes and incentives, to increase the amount of used oil being re-refined.

6.2.6 Used Oil Collection and Transport Reporting

California, like most states, requires that used oil collectors and transporters maintain records and provide periodic reports. Most other states surveyed require a written report. However, California State provides a short electronic form for this purpose.

In addition to the mandatory state reports, both collectors and transporters are required to maintain detailed logs of their activities for periods of three years.

6.2.7 Greenhouse Gas Credits

California was the first state which passed legislation to limit greenhouse gas production from manufacturing and refining operations (California State Legislature 2006. Assembly Bill 32). The legislation was in the form of a cap-and-trade system in which marketable carbon dioxide credits will be allocated to manufacturers and refiners. In a petroleum production or re-refining process, greenhouse gases are derived primarily from the combustion of hydrocarbons. As such, they will closely follow process energy use. Because re-refining used oil requires significantly less energy than manufacture of base oil from virgin petroleum, it will produce significantly lower amounts of greenhouse gases. Implementation starts January 2009.

Until the California State cap-and-trade system becomes effective, it is not possible to predict either the carbon dioxide cap or the market value of carbon dioxide credits allocated to a process.

6.2.8 Regulation as a Recycled Product

California State does not appear to provide guidance additional to that given by the U.S. Environmental Protection Agency. The EPA indicates that 25% re-refined base oil qualifies for preferred status as a recycled product. However, it is possible that California will require a higher standard because it is achievable and would result in re-refining and use of a significantly larger amount of re-refined base oil. For example, the Defense Logistics Agency typically posts its re-refined base oil fraction as 90%.

6.2.9 Grants for Educational and Scientific Studies of Used Oil

California State, through the California Integrated Waste Management Board, provides funding for a variety of educational projects. These are primarily designed to increase: 1) the amount of used oil taken by citizens to collection centers, 2) awareness of pollution from used oil, and 3) ease of public access to information on the state's used oil program.

The state also funds a number of studies by universities, research institutions, and marketing agencies. These are typically commissioned to provide information for state regulatory and legislative staff, develop marketing programs, and meet requirements imposed by the state's governor and legislature.

Altogether, the website indicates that the grant program, at over a million dollars per year, is well funded.

6.3. IMPACT OF FEDERAL AND STATE REGULATIONS

The most significant federal change is the Environmental Protection Agency rule EPA503-F-08-006. This excludes used transportation lubricants from RCRA solid wastes if the oil is being collected or transported with intention of closed-loop recycling. This means that, barring evidence to the contrary, used oil can be treated as a non-hazardous material. As it went into place at the end of 2008, this ruling is extremely favorable to used oil re-refining because it specifically classifies used oil intended for combustion as a potentially-hazardous solid waste.

Other federal regulations are, for the most part, also extremely favorable to use of re-refined of transportation lubricating oil. For example, Executive Order 13423 (2007) requires: 1) all federal agencies and their contractors to preferentially purchase re-refined oil and other recycled products (without consideration of cost or substantial equality); 2) all federal agencies and their contractors to reduce their consumption of non-recycled petroleum products by 2% per year; and 3) a 30% reduction in energy intensity by 2015, relative to 2003 use (or a 3% reduction in energy intensity per year relative to 2003, reaching 30% reduction by 2015).

The impacts of California state regulations were also considered. California is a complex, environmentally-fragile state which often leads the rest of the country in implementation of environmental and energy regulations. Several major trends in California State used oil recycling were evaluated by Lawrence Livermore National Laboratory in 2008. Although their report preceded the federal ruling, California's Integrated Waste Management Board was considering favoring the use of re-refined oil over downcycled, single use products such as marine distillate oil and recycled fuel oil. With the new federal rulings, California State is likely to take these actions to minimize combustion of marine distillate oil and recycled fuel oil: 1) minimize combustion permits for these two products, and 2) increase the current $0.16 per gallon fee currently collected on virgin oil products and transferred to used oil collection centers.

The California Assembly has passed, and the governor signed into law, regulations supporting a cap-and-trade system for greenhouse gas emissions. This system would be very favorable to used oil re-refining in that its lower process energy requirements result in marketable credits.

California, however, also discourages re-refining of used oil in a number of significant ways. First, it is extremely difficult to obtain a permit to build a new re-refining plant or to extend an existing plant. Permitting for the new Evergreen Oil plant required seven years. Second, California requires chemical analysis of used oil. This is an important step in environmental protection, but is also extremely costly (as high as $0.50/gallon). Additionally, most other states indemnify collectors and transporters of used oil against a small number of "contaminated batches" per year.

California is also considering requiring analyses for batches of oil transported to another state for recycling or re-refining. The intent of this measure is to make it expensive to re-refine outside of California State. However, the cost of analyses is high relative to the value of the oil re-refined. The impact is a significant increase in the cost of re-refining oil which is transferred to consumers and a significant decrease in the profitability of re-refining oil.

7. CONCLUSIONS ON POTENTIAL ENERGY AND ECONOMIC BENEFITS FROM PETROTEX HYDROCARBONS, LLC., OIL REGENERATION

This report presents an assessment of the potential benefits from the ReGen™ oil re-refining process developed by PetroTex Hydrocarbons, LLC. PetroTex Hydrocarbons, LLC., has performed extensive pilot scale evaluations, computer simulations, and market studies of this process and is presently evaluating construction of a 23 million gallon per year industrial-scale plant at a site in Midlothian, Texas. PetroTex has obtained a 30 acre site in the Texas Industries RailPark in Midlothian Texas. The environmental and civil engineering assessments of the site are completed, and the company has been granted a special use permit from the City of Midlothian and air emissions permits for the Texas Commission on Environmental Quality.

The impact of constructing these facilities on local employment is significant. If the plant size remains constant, each plant could create 1400 construction jobs and employ a permanent staff of 28. Additionally, transportation of used oil to the re-refinery will require approximately 12 truck drivers.

There is an excellent chance that the PetroTex Hydrocarbons, LLC., ReGen™ re-refining process, which includes both solvent extraction and hydrofinishing, will be successful. The major reasons for this are its process flexibility and high process integration.

The ReGen™ process provides high energy yields in the forms of process and marketable fuels, as well as a high yield of at least two grades of base oils from the used oil. The process was developed to minimize purchased process energy.

The ReGen™ process has higher returns on investment and shorter payout times in comparison to a recent analysis of worldwide oil re-refining processes. Results of a sensitivity analysis showed that, unless the crude oil price remains below $50 per barrel for extended periods, payout times are less than two years. The analysis showed a profit down to a crude price of about $21/barrel.

The market for the base oils is significant. Sales of lubricants in the U.S. were above 10 Billion dollars in 2005 and many of the establishments that produce lubricants purchase, rather than manufacture, the base oils from which they are blended.

The success of a limited number of industrial scale competing processes has established the utility of re-refined base oils in conventional transportation lubricants and has also shown that re-refining lubrication base oils is acceptable to customers and is, typically, profitable.

Many states have established programs which facilitate collection of used, or waste, oil from vehicles. The federal government, in particular the Defense Logistics Agency, and some states are interested in supporting “closed-loop” oil recycle programs in which the base oils in transportation lubricants are recovered, re-refined, and recycled back into transportation lubricants.

The transportation oil re-refining processes currently fielded at industrial scale are, with one exception, based on the Mohawk process developed in the 1980s. These processes are relatively straightforward and have been used by Evergreen Oil, Inc. and Safety-Kleen for two decades.

A new plant, based on the simplified Mohawk-Evergreen process and constructed by Heartland Petroleum to treat the waste oil from the Lube Stop chain has found good customer acceptance of lubricating oils with a high recycled content. The Lube Stop chain has been able to charge a premium for its re-refined oil products.

Re-refining of used domestic oil is expected to increase in the next decade. Refining waste oil in the U.S. decreases the need to purchase foreign-produced base oils and, additionally, creates domestic jobs.

Use of re-refined base oils could also minimize both energy and greenhouse gases emissions. Combustion, rather than re-refining, is the major current use for waste lubricating oils. Re-refining minimizes greenhouse gas emissions both by decreasing the energy required to produce oil and by providing an alternative to burning waste oil.

The conventional lubricant market encourages the use of recycled and re-refined base oils because most of the manufacturers are small businesses which purchase and blend base oils and additives. The diversity and profitability of lubricant manufacture both prevent market domination by a limited number of large companies and encourage the use of recycled and re-refined base oils in finished products.

The most significant federal change is the Environmental Protection Agency rule EPA503-F-08-006. This excludes used lubricants from being considered as solid wastes under the Resource Conservation and Recovery Act if used oil is being collected or transported with intention of closed-loop recycling. This means that, barring evidence to the contrary, used oil can be treated as a non-hazardous material. As this decision went into place at the end of 2008, the rule specifically classifies used oil intended for combustion as a solid waste. This ruling is extremely favorable to used oil re-refining.

Other federal regulations are, for the most part, extremely favorable to use of re-refined of transportation lubricating oil. A 2007 presidential executive order: 1) requires all federal agencies and their contractors to preferentially purchase re-refined oil and other recycled products (without consideration of cost or substantial equality); 2) requires all federal agencies and their contractors to reduce their consumption of non-recycled petroleum products by 2% per year; and 3) relative to 2003, requires a 30% reduction in energy intensity by 2015 (or a 3% reduction in energy intensity per year relative to 2003, reaching 30% reduction by 2015).

Re-refining reduces carbon dioxide 78% in comparison to the original refining process which produced lubricating base oil from virgin petroleum. The California Assembly has passed, and the governor signed into law, regulations supporting a cap-and-trade system for greenhouse gas emissions. Assemblies of other coastal states have or are considering similar legislation. This system would be very favorable to used oil re-refining in that its lower process energy requirements result in marketable credits.

8. BIBLIOGRAPHY

Arner, R. 1992. *Used oil recycling markets and best management practices in the United States*. Annadale, VA: Northern Virginia Planning District Commission

American Petroleum Institute. 2008. *Lubricating Oil Interchangeability Guildelines, Appendices E and F*. From website.

Audibert, F. 2006. *Waste engine oils: re-refining and energy recovery*. Amsterdam: Elsevier.

Bacha, J.; Barnes, F.; Franklin, M.; Gibbs, L.; Hemighaus, G.; Hogue, N.; Lesnini, D.; Lind, J.; Maybury, J.; and Morris, J. 2000. *Aviation fuels technical review*. Chevron Products Company report FTR-3.

Bruening, J. C. 1995. Filters seek recycling niche. *Recycling today*, April.

Bush, G. W. 2007. Strengthening federal environmental, energy, and transportation management. *Federal Register* 72(17): 3919-3923. Executive order 13423.

California State Legislature. 2006. *The California Global Warming Solutions Act of 2006*. Assembly bill 32.

Census Bureau. 2004a. *Annual survey of manufactures: 2002 and earlier years*. From U.S. Department of Commerce website.

Census Bureau. 2004b. *Petroleum, lubricating oil, and grease manufacturing: 2002*. U.S. Department of Commerce report EC02-311-324191 (RV).

Census Bureau. 2006. *Annual survey of manufactures: 2005 and earlier years*. From U.S. Department of Commerce website.

Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms. 2001. More capable warfighting through reduced fuel burden. Office of the Under Secretary of Defense for Acquisition, Technology and Logistics.

Dimotakis, P.; Grober, R.; and Lewis, N. 2006. *Reducing DoD Fossil-Fuel Dependence*. MITRE corporation report JSR-06-135.

Donovan, A. 1994. *Environmental regulations and technology: managing used motor oil.* Environmental Ptrotection Agency report EPA/625/R-94/010.

Energy Information Administration. 2008. *Annual Energy Review – 2007*. U.S. Department of Energy report DOE/EIA-0384.

Environmental Protection Agency. 2007. *Comprehensive procurement guidlines. Buy Recycled Series. Vehicular Products*. Environmental Protection Agency publication EPA530-F-07-042.

Fehrenbach, H. 2005. *Executive summary. Ecological and energetic assessment of re-refining used oils to base oils: substitution of primarily produced base oils including semi-synthetic and synthetic compounds*. Heidelberg, Brussels: Institute für Energie-und Umweltforschung.

Fehrenbach, H. 2005. *Final report. Ecological and energetic assessment of re-refining used oils to base oils: substitution of primarily produced base oils including semi-synthetic and synthetic compounds*. Heidelberg, Brussels: Institute für Energie- und Umweltforschung

Green, C. 2000. Recycling a costly commodity. *Recycling today*. September.

Green, C. L. 2008a. U.S. base oil price report. *Lube report* 8(1).

Green, C. L. 2008b. U.S. base oil price report. *Lube report* 8(53).

Industrial Technologies Program. 2007. *Stage-gate innovation management guidelines, V. 1.3*. U.S. Department of Energy, Energy Efficiency and Renewable Energy report.

JASON. 2006. *Reducing DoD fossil-fuel dependence.* The MITRE Corporation report JSR-06-135.

Kajdas, C. 2000. Major pathways for used oil disposal and recycling. Part 1. *Tribotest* 7(1): 61-74.

Kajdas, C. 2000. Major pathways for used oil disposal and recycling. Part 2. *Tribotest* 7(2): 137-153.
Lawrence Livermore National Laboratory. 2008. *Improving used oil recycling in California*. State of California Integrated Waste Management Board publication #610-08-008.
Meredith, C.; Warchol, D.; Groch, P. 2005. *UOMA program review final report*. Edmonton, AB, Canada: BearingPoint LP.
Mueller Associates, Inc. 1987. *Waste oil: technology, economics, and environmental, health, and safety considerations*. Department of Energy report DOE/EV/10450-H2.
Nagler, B. 2004. Crude attempts. *Recycling today*, May: 88-93.
Nixon, H., and J.-D. Saphores. 2003. *The impacts of motor vehicle operation on water quality: a preliminary assessment*. University of California, Irvine, Institute of Transportation Studies report UCI-ITS-WP-03-01.
Office of Fossil Energy. 2006. *Used oil re-refining study to address Energy Policy Act of 2005, Section 1838*. U.S. Department of Energy report. Sullivan, T. 2002. Base oil price report. *Lube report* 2(1).
Stitzel, D., and T. Spille. 1995. Calling all cars. *Resource recycling*, March: 60-65.
Sullivan, T. 2003. Base oil price report. *Lube report* 3(1).
Sullivan, T. 2004. Base oil price report. *Lube report* 4(1).
Sullivan, T. 2005. Base oil price report. *Lube report* 5(1).
Sullivan, T. 2006. Base oil price report. *Lube report* 6(1).
Sullivan, T. 2007. Base oil price report. *Lube report* 7(1).
Tocci, L. 2008. Fuchs: Lube demand swings up. Lube Report 8(4).
Urbanchuk, J. M. 2008. *Contribution of the ethanol industry to the economy of the United States*. Report prepared for the Renewable Fuels Association.
U.S. Department of Health and Human Services, Public Health Services, Agency for Toxic Substances and Disease Registry. 1997. *Toxicological profile for used mineral-based crankcase oil*. Atlanta, GA: Agency for Toxic Substances and Disease Registry. (Note: human authors are: A. S. Dorsey, Jr.; C. Rabe; S. Thampi)
U.S. Tank-Automotive and Armaments Command. 2004. *Performance Specification. Lubricating oil, internal combustion engine, combat/tactical service*. Military specification MIL-PRF-2104H.