RECYCLING, OIL

1. Introduction

The term oil includes a variety of liquid or easily liquefiable, unctuous, combustible substances that are soluble in ether, but not in water, and that leave a greasy stain on paper and cloth. There are three classes of oil; (*1*) fatty or fixed oils of animal or vegetable origin (triglycerides), (*2*) essential or volatile oils mostly of vegetable origin, and (*3*) mineral oils (chemically, mixtures of hydrocarbons). An oil that has been used or contaminated, or both, but not consumed, can often be recycled to regain a useful material, regardless of its origin. For the purposes of this article, only the recycling of used mineral oil products, which tend to be derived from petroleum crude oil, is considered.

Historically, used or contaminated oil was considered a waste. Means of disposal included incineration, road oiling, landspreading, municipal landfills, and dumping onto the ground or into storm sewers. More recently, growing public awareness of the societal costs of pollution, the advent of periodic petroleum shortages, increased reliance on exports, and rising prices for most kinds of oils and oil products have combined to generate a strong interest in developing ways to conserve the valuable energy and resource content of these products.

The following definitions are useful to the discussion of oil recycling (1):

Used Oil. Oil whose characteristics have changed since original manufacture and that is suitable for recycling. This is an umbrella category that includes used lubricating oils of all types as well as dirty or contaminated fuel or other oils that can be economically recycled.

Waste Oil. Oil having characteristics that make it unsuitable for further use or economic recycling. This material may be usable as a fuel in large industrial furnaces, such as cement kilns.

Oil Recycling. The acquisition and processing of oil that has become unsuitable for its intended use in order to regain useful material.

Oil Reclaiming, Laundering, or Reconditioning. The use of cleaning methods during recycling, primarily to remove insoluble contaminants, making the oil suitable for further use, usually in the same or similar role as its original use. Methods may include settling, heating, dehydration, filtration, and centrifuging. The product is reclaimed oil.

Oil Reprocessing. The preparation of used oil to be suitable as a fuel. The techniques used are similar to those for reclaiming (2).

Oil Re-Refining. The use of refining processes during recycling to produce high quality lubricating base stock for lubricants or other petroleum products. Re-refining may include distillation, hydrotreating, and treatments employing acid, caustic, solvent, clay, and/or other chemicals. The product is re-refined lubricating base stock.

Recycling lubricating oils has existed as an industry since the late 1920s. At that time, lubricating oils contained few or no additives (chemical compounds added to oils to improve lubrication characteristics such as wear, oxidation, and corrosion) (see LUBRICATION AND LUBRICANTS). Recycling these oils usually involved some combination of heating to remove volatile components; settling to separate water, dirt, and sludge; and centrifuging or filtering to remove most of the remaining insoluble contaminants. By this limited processing, lubricating oils could be recycled to essentially original oil quality. Modern lubricating oils are more sophisticated and functionally diverse. Containing up to 20% or more by volume of complex additives, these oils present increased recycling challenges (3).

Worldwide production of lubricating oil is estimated at 4.3×10^7 m^3/year (11.2×10^{10} gal/year) (4). Table 1 shows the approximate breakdown by region (5). Lubricating oil sales in the United States since the 1970s have remained relatively steady at $9.5 \times 10^6 m^3$/year (2.5×10^9gal/year). Of these volumes, automotive lubricants and industrial/process lubricants each represent approximately one-half (6-8). The industrial lubricants category includes the following types: hydraulic, quenching, cutting, metalworking, electrical, and process oils.

In the United States, it is estimated that ~70% of the original volume is recoverable (of sufficient quality and quantity to make it practical to collect and process it), but only 40% is actually collected each year (9). Of that, ~7% is re-refined into motor oil, ~17% is reclaimed into industrial oil, and most of the remainder is burned as a fuel oil, often undergoing little processing to remove contaminants (10,11). The large quantity not collected illustrates the significant pollution potential represented by improperly managed used oil.

To help differentiate the severity of processing, used oil recyclers are often divided into three categories: reclaimers who recover industrial oils from segregated oils, usually for reuse in the oils' original application; reprocessors who process used oil for reuse as a fuel; and re-refiners who produce base oil for blending a wide variety of lubricants. In many cases, an oil recycler is involved with more than one of these categories.

There are ~200 oil recyclers in North America. Of these, only three are primarily re-refiners, which take the oil to be recycled through the entire refining process. In Europe, there are 21 re-refiners (12) and worldwide there are ~400 oil re-refining plants using a variety of technologies with an overall capacity of 1800 kt/year (13). There are many more companies involved in oil recycling utilizing less complex processes.

Recycled lubricating oil products are potentially suitable for all uses, including their original use, if given proper segregation, cleanup, and additive treatment, because the basic hydrocarbon structure is not significantly altered during most uses (3,14,15). Studies have been done to demonstrate that re-refined oils using modern technology produce a safe product, including consideration of carcinogenicity (16). Although nontechnical factors such as economics and availability determine whether all potential uses for recycled oil can be made available on a realistic basis, energy and natural resource conservation, pollution control, and increasingly strict regulatory climates all contribute to the support of effective oil recycling.

2. Characteristics of Used Oils

Used petroleum oils to be recycled can be obtained from a variety of sources, including automotive garages and service stations, quick lube change franchises, truck and taxi fleets, military installations, individuals, industrial plants and manufacturing facilities. The main types of used petroleum oils that are recycled are internal combustion engine lubricants and hydraulic and industrial oils. The additives and contaminants typical in these used oils can cause both performance-related and environmental problems (14,17–21). Further, used oils may often be comingled with each other and with water, solvents, and other chemicals before being collected for recycling. Much of the easily recoverable used oil is employed as fuel that has undergone little or no processing for contaminant removal (6,7).

Chemical analyses have been performed on used and waste oils, primarily for inorganic constituents. These analyses have been described in the literature (6,17,19,21–23) and are summarized in Table 2. The data show that used oils contain contaminants that often should be removed during the recycling process to protect the environment. However, many organic contaminants contained in such oils are often not analyzed. In particular, polychlorinated biphenyls (PCBs), are strictly regulated in used and waste oils at concentrations $\sim$50 ppm (0.005 wt%) and to as low as 2 ppm (0.0002 wt%) depending on the applications. The PCBs are often not determined in used or waste oils, even though they sometimes occur in these oils (6,7) (see CHLOROCARBONS AND CHLOROHYDROCARBONS, TOXIC AROMATICS). In the United States, regulations on PCBs are established by the Toxic Substances Control Act (32); additional U.S. regulations are based on hazardous waste provisions in the Resource Conservation and Recovery Act (33). Chlorinated solvents are found frequently, usually as a result of contamination of the used oil during storage prior to recycling (18).

Data published by the U.S. EPA in 1991 documented the effect of unleaded gasoline on lead levels in used oil. In addition, this EPA study focused on specific chlorinated solvents and polynuclear aromatics (PNAs). In the United States, these compounds are considered when deciding whether used oil must be handled as hazardous or nonhazardous waste (34). Table 3 provides a summary of some typical contamination levels found in recent testing of used oils primarily from the vehicular markets. Some contaminants, such as chlorinated solvents, are picked up by the used oil after application and during storage waiting for collection. However, not all chlorine found in used oil is necessarily the result of contamination; small amounts (up to hundreds of ppm) may have come from additives in the original product. Typical contaminant levels found in used industrial lubricating oils are given in Table 4.

3. Technology

In the recycling of used oils to regain useful products, a number of processing steps are possible, depending on the original source of the used oil, the level of contamination, the sophistication of the recycling technology available, and the requirements for the end product. Three levels of recycling are briefly described herein. In general, oil cannot be recycled to a higher quality product than its original use. For example, low or medium viscosity index (VI) industrial oil cannot be recycled into high VI automotive engine oil. Further, it is important for cost-effective oil recycling to keep different oils segregated during the recycling process, because commingling of high VI with low VI used oil allows only recycling into low VI, often low value, products.

3.1. Reprocessing. Combustion of used oil as burner fuel has often been condemned because it destroys a valuable resource (lube oil basestock) and can cause substantial environmental pollution through widely dispersed distribution of sulfur, nitrogen and metal oxides, volatile organic contaminants, and particulate matter. Further, these contaminants, sometimes referred to as products of incomplete combustion, may cause scaling of heat-transfer surfaces and fouling of burners and fuel-transfer lines if not handled or processed properly. However, under certain conditions and using suitable precautions, the recovery of the energy as heat is a valid used oil disposal option (3,10,24,35). The conditions and precautions for burning used oil have been described (17); typical regulatory standards can also be found (36); and specifications now exist for industrial and commercial grades of boiler fuels made from used oils (2,37).

Processing techniques for the recycling of used oil into fuel include pretreatment of the used oil to remove all or most of the contaminants that cause environmental or operational concerns. Least rigorous pretreatment options include settling or centrifugation, or both, to remove coarse solids and free water. Improved cleaning occurs when using heat and demulsifiers to remove water, volatiles, and most suspended solids. However, these methods do not significantly reduce the soluble contaminants or submicrometer-sized particulates that contribute to ash formation. More rigorous treatments of used oil (such as simple distillation) can be applied to further clean the oil, but are not normally employed for economic reasons. An alternative approach is to subject the used oil to minimal reprocessing followed by burning in specialized facilities using acceptable environmental control, eg, electrostatic precipitators, Venturi scrubbers, or a fabric filter baghouse (17).

3.2. Reclaiming. Used oils can be reclaimed or reconditioned within the user facility or sent outside the facility to a commercial reclaimer. The primary difference between these two options is usually the level of treatment available. Often the in-plant reclaiming facility is limited to gravity purification or settling, filtration, centrifuging, and heating to remove volatiles and water. A commercial reclaimer can usually perform all of these as well as providing clay treatment, chemical treatment (primarily with acids or bases), demulsification, and distillation. Both options usually include reformulation with additives, as necessary for reuse in the original application. A general description of such processes may include any or all of the following: (*1*) removal of solid particles by settling, centrifuging, or filtering; (*2*) neutralization of acidic components with clay or alkalis, and removal of resulting soaps by washing; (*3*) heating–distillation to remove volatile solvents, gasoline, and water; (*4*) clay contacting to remove oxygenated components and spent additives or for decolorization; (*5*) aeration and use of biocides to reduce bacterial levels; and (*6*) replenishment of additives.

The product of a reclaiming procedure is reclaimed oil, which often meets original specifications for such uses as hydraulic fluids, gear lubricants, cutting and grinding oils, and metal-rolling lubricants. Perhaps the most important requirement for effective reclaiming is segregation of the used oils according to type. In general, a mixture of high and low quality oil can be reclaimed only as low quality oil or as fuel. Thus, the lack of segregation at the source may carry a high economic penalty.

3.3. Re-Refining. Petroleum refining techniques are employed for re-refining used lubricating oil to produce clean, high quality lubricating base oil. The process often includes pretreatment to reduce the impurity content by one or more of the following methods: application of heat, filtration, and treatment using acid, caustic, solvents, and/or other chemicals. In developed countries, pretreatment is usually followed by multistage vacuum distillation and catalytic hydrogenation as a finishing step as shown in Fig. 1 (3).

Countries having less stringent environmental regulations continue to allow treatment using concentrated sulfuric acid and large amounts of clay followed by plate-and-frame filtration. There is also scattered use of chemical pretreatment followed by hydrotreating, solvent extraction using clay or hydrogen finishing, and extensive treatment using only clay; the last being limited to highly segregated used oil (38–41). The recent publication of an international guide for characterizing lubricant base oils has officially placed virgin and re-refined base oils on the same scale, and acknowledges the ability of modern re-refineries to produce high quality base oils (42). Thus, the current market for re-refined oil is driven by environmental and economic pressures, not quality issues (43).

Many re-refining processes are described in the literature (36–41,44). New technologies have been proposed and patented, although there are concerns with many of these newer re-refining approaches regarding the lack of technical data and long-term experience establishing the quality of the re-refined base oil product. Additionally, some economic assessments underscore the viability of the distillation–hydrotreat approach (40,45). Nonetheless, the environmental and economic drivers for accessible technologies to support responsible waste management have encouraged and continue to encourage research and development in this area. This subject is discussed in great detail in several publications (7,12,15,29,30,35,38-41,44,46).

4. Regulations and Specifications

A significant source of concern for potential users of recycled petroleum products has been the lack of specifications or certifications related to the quality of the material and the consistency in producing high quality products. This perception of possible inferiority has been exacerbated by the reluctance of some equipment manufacturers to state whether they would honor warranties if recycled lubricants were used.

The literature is full of detailed evaluations of recycled petroleum products (3,14,29,30,35,44), investigations into the environmental ramifications of the recycling processes themselves (15,21,47). Product specifications have been issued by such organizations as the Canadian General Standards Board (48) and ASTM International (42).

The thrust of these actions is to require the recycled petroleum products to meet the same requirements as placed on their virgin equivalent, as well as to demonstrate that contaminants have been reduced to insignificant levels.

Based on the evidence that acceptable recycled petroleum products can be produced, there is a considerable legislative record encouraging the recycling of used oil. Starting with the U.S Resource Conservation and Recovery Act in 1976 (33), used oil was held apart from the normal hazardous waste system, because the oil was viewed as a valuable commodity. This was followed by the U.S. Used Oil Recycling Act in 1980 (49), which removed any federal requirement that lubricants containing re-refined base oil carry special labeling.

The U.S. EPA issued regulations implementing the legislation in stages, starting in 1988 with a Guideline for Federal Procurement of Lubricating Oils Containing Re-refined Oil (50) and concluding with Management Standards in 1992 (36). As part of the latter, the EPA chose not to list used oil as a hazardous waste in order to encourage its collection and recycling. These regulations have been compiled into Part 279 of Volume 40 of the U. S. Code of Federal Regulations (40CFR279).

The U.S. Federal Trade Commission announced a rule, effective November 30, 1995, that sets test procedures and labeling standards for recycled oil used as engine lubricating oil (51). The test procedures used are those contained in the Engine Oil Licensing and Certification System of the American Petroleum Institute (API) (52). The rule states, in effect, that if recycled oils meet the requirements of the API Certification System, such oils are substantially equivalent to new oil for use as engine oil. This federal rule pre-empts certain state recycled oil rules (51).

In other countries around the world, local, state/provincial, and federal governments have also taken legislative action to encourage and support responsible used oil management (12,15,46,53–55). The most frequent forms of support are penalties for improper disposal and tax or grant incentives to encourage the return of used oil to recyclers. Government tracking of used oil through transport manifest programs and recycling facility permitting and auditing requirements also figure heavily in most developed countries' legislation. Some governments, recognizing the equivalency of lubricants made from re-refined base oil to those made from virgin base oils, have special directives that lubricants used by government agencies should include some portion of re-refined base oil content.

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Table 1. **Worldwide Production of Lubricating Oil**

Region	Estimated Lubricant Market, 2003 billion gal/million tones
North America	2.7/8.9
Central and South America	1.0/3.2
Western Europe	1.5/5.1
Central/Eastern Europe	1.4/4.9
Near/Middle East	0.6/2.0
Africa	0.6/1.8
Asia Pacific	3.4/11.2

Table 2. **Summary of Reported Used Oil Analyses**[a]

Property or test	Motor oils	Industrial oils[b]
viscosity, at 40°C, SUs	87–837	143–330
API gravity, at 15.6°C	19.1–31.3	25.7–26.2
specific gravity, 15.6/15.6°C	0.9396–0.8692	0.9002–0.8972
water, vol %	0.2–33.8[c]	0.1–95
bottom sediment and water, vol %	0.1–42	
benzene insoluble, wt %	0.56–3.33	
gasoline dilution, vol %	2.0–9.7	
flash point, °C	79–220	157–179
heating value, MJ/kg[d]	31.56–44.88	40.12–41.84
ash, sulfated, wt %	0.03–6.43	3.2–5.9[e]
carbon residue, wt %	1.82–4.43	
fatty oil, wt %		0–60
chlorine, wt %	0.17–0.47	<0.1–0.83
sulfur, wt %	0.17–1.09	0.54–1.03
zinc, ppm	260–1787	
calcium, ppm	211–2291	
barium, ppm	9–3906	
phosphorus, ppm	319–1550	
lead, ppm	85–21,676	
aluminum, ppm	<0.5–758	
iron, ppm	97–2401	

[a] Data taken from Refs. (6, 14, 22–30) did not provide data on all tests listed; therefore, data may be inconsistent between different tests.
[b] Limited data were available for used industrial oils; see Ref. 6.
[c] One sample had a water content of 46.5 wt % but is considered an outlier.
[d] To convert MJ/kg to Btu/lb, multiply by 430.4.
[e] Values for the industrial oils were stated to be for the regular, not the sulfated ash.

Table 3. **Summary of Typical Vehicle Used Oil Contaminant Levels**[a,b]

barium[c]	10
cadmium	0
chromium	8
lead	30
trichloroethylene	3
perchloroethylene	60
trichloroethane	80
benzo[*b*]fluoranthene	9
benzo[*k*]fluoranthene	6
benzo[*a*]pyrene	10
sulfur	3000

[a] In parts per million (ppm).
[b] All data from Ref. 31, except where noted.
[c] From Ref. 16.

Table 4. **Summary of Typical Industrial Used Oil Contaminant Levels**[a]

	Used oil type[b]		
Property or test, ppm	HF	MWF	EIO
arsenic	3.26	2.0–21.5	<1
barium	1.4–460	0.3–8.1	<1
cadmium	1.4–10.1	1.3–4.8	<0.25
chromium	1.0–1.6	1.0–5.4	<1
lead	1.0–7.0	1.0–6033	1.0
benzene	ND	<5	<5
trichloroethylene	ND	<5	<5
perchloroethylene	ND	<5	<5
trichloroethane	ND	<5	<5
tetrachloroethane	ND	<5	<5
benzo[*b*]fluoranthene	<5	6	<5
benzo[*k*]fluoranthene	<5	<5	<6
benzo[*a*]pyrene	<5	<5	<5
PCBs	ND	ND	6.9

[a] Ref. 34.
[b] Hydraulic oil/fluids = HF; metalworking oil/fluids = MWF; electrical insulating oils = EIO; and not detected = ND.

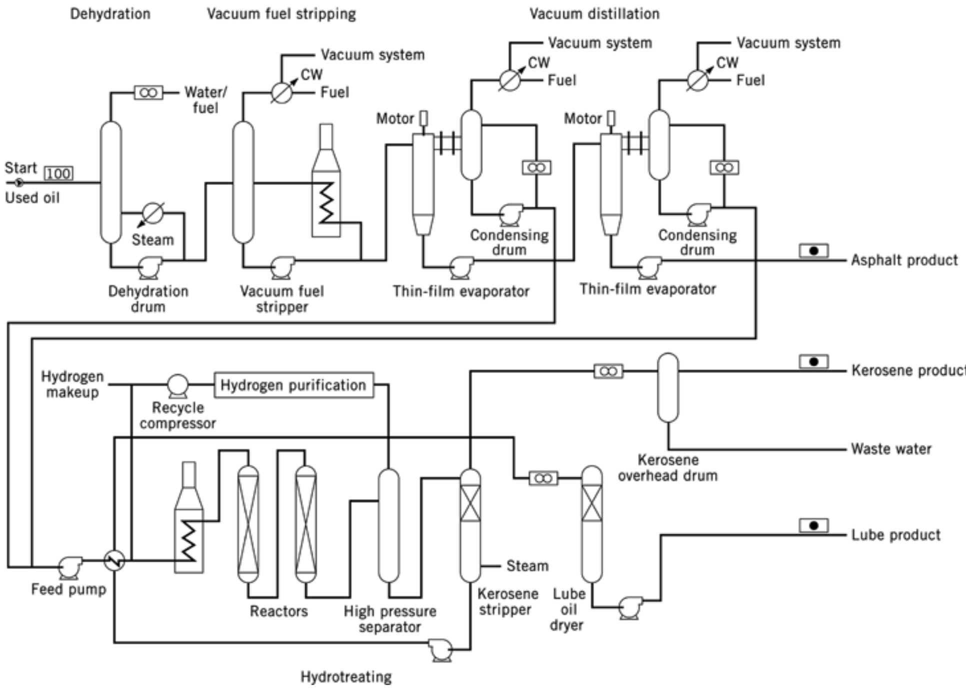

Fig. 1. Distillation–hydrotreat process, where CW = cooling water.