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Global Emissions of Carbon Dioxide from Petroleum Sources

HEALTH AND ENVIRONMENTAL AFFAIRS
DEPARTMENTAL REPORT NUMBER DR 141
1991

Reprinted in 1993

American Petroleum Institute
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Washington, D.C. 20005



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Global Emissions of Carbon Dioxide from Petroleum Sources

**Health and Environmental Affairs
Departmental Report No. DR 141**

PREPARED UNDER CONTRACT BY:

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JULY 1991

**American
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1.0 INTRODUCTION

The analysis and interpretation of recent atmospheric, oceanographic, and earth sciences data suggests that significant changes in current global climate patterns may occur as a result of the accumulation of carbon dioxide (CO₂) and other greenhouse gases in the Earth's atmosphere. The nature of area- or region-specific climate shifts are still uncertain with regard to type (i.e., temperature change, precipitation modification, change in frequency of severe storms, sea level fluctuations, etc.), magnitude, and timing. Given the possible severe and irreversible consequences of climate change to global socio-economic parameters, further study of greenhouse gas emission rates and emission reduction techniques is warranted.

Carbon dioxide is hypothesized to contribute approximately half of the increasing concentrations of greenhouse gases that are potentially creating shifts in global climate patterns. The atmospheric concentration of CO₂ has increased from about 280 ppm in 1800 to 353 ppm in 1990 (Houghton et al., 1990). The current rate of increase in atmospheric CO₂ concentration is 0.5 percent per year (Houghton et al., 1990). Although natural exchanges of CO₂ between the atmosphere and the biosphere (oceans, biomass, soils) are estimated in excess of 200 billion tons per year of carbon, the current 5.5 billion tons of carbon emissions (equivalent to 20.2 billion tons of CO₂) resulting from fossil fuel combustion is thought to be a primary factor in the rise in atmospheric CO₂ concentrations in the past 180 years (Lashof and Tirpak, 1989). Between 0.4 and 2.6 billion tons of carbon emissions (1.5 to 9.5 billion tons of CO₂) are attributed to deforestation.

The largest sources of anthropogenic CO₂ are from fossil fuel combustion, including coal, oil, and natural gas. Coal and oil each contribute about 40 percent with natural gas

contributing about 20 percent to the total fossil fuel emissions of CO₂. Because of the large part CO₂ plays in estimates of total climate change potential, coal and oil can each be expected to contribute about 20 percent of the total change. Consequently, the examination of the energy industries is important in understanding the emissions from such sources in terms of potential impacts to global climate change.

The International Panel on Climate Change (IPCC) has concluded that increases in CO₂, methane, and other greenhouse gases will promote climate change (Houghton et al., 1990). The objective of this report is to present estimates of CO₂ emissions from all segments of the global petroleum industry. These estimates are based on available data associated with individual petroleum industry segments. CO₂ emission estimates for certain regions and/or industry segments that were calculated from incomplete or otherwise inadequate data are identified. Emissions associated with the coal and natural gas industries are not presented.

2.0 EXECUTIVE SUMMARY

In this study, CO₂ emission estimates have been developed for a broadly defined petroleum industry that encompasses everything from locating oil reserves through end uses of the oil products. The industry has been divided into five major segments: (1) exploration and extraction, (2) crude petroleum transportation to refineries, (3) refining operations, (4) refinery products transportation, and (5) end uses. Carbon dioxide emission estimates have been developed for each industry segment for each country by multiplying an activity factor by an emission factor. Activity factors describe the activity level for a particular industrial activity such as crude transportation. The units of measure selected for activity factors were those for which country-specific data were available or could be calculated. For example, barrel-miles were used for crude transportation and barrels of throughput were used for refinery operations. Corresponding emission factors for each activity factor were developed from EPA and industry documents.

The results of this report are global estimates of CO₂ emissions by industry segment and by country and region. The global petroleum industry segment with the largest estimated total emissions is end uses with 8.4 billion tons per year of CO₂ emissions or almost 91 percent of the total. Refinery operations had the second highest emissions with 0.5 billion tons per year of CO₂ emissions or 6 percent of the total. North America was clearly the largest CO₂ emitting region with nearly 30 percent (2.83 billion tons per year) of the total global CO₂ emissions generated by the petroleum industry.

These results generally agree with other estimates for global petroleum industry CO₂ emissions. The draft EPA report to Congress entitled "Policy Options for Stabilizing Global Climate" (Lashof and Tirpak, 1989) gave an estimate of 8.1 billion tons of CO₂ emissions per year from oil consumption. This estimate includes the end use segments reported

here and portions of the remaining industry segments. When considered on an equivalent basis, the estimate from this report is approximately 12 percent higher than the EPA estimate. The results of this report have also been compared to results from the Edmonds-Reilly global CO₂ emissions model (Edmonds and Reilly, 1983). Their model predicted 1987 global CO₂ emissions from oil to be 8.9 billion tons per year. When considered on an equivalent basis, the CO₂ total emissions estimate reported here is within 3 percent of the Edmonds-Reilly model prediction. Data were not available for all countries. The fractional contributions of CO₂ emissions from reported countries would slightly decrease given the small increase in total global emissions if data were available for every country.

The technical overview of the petroleum industry is limited to basic descriptions and definitions of the identified industry segments and associated processes for which emission factors were derived (Figure 2-1). The geographic regions considered are also presented (Figure 2-2).

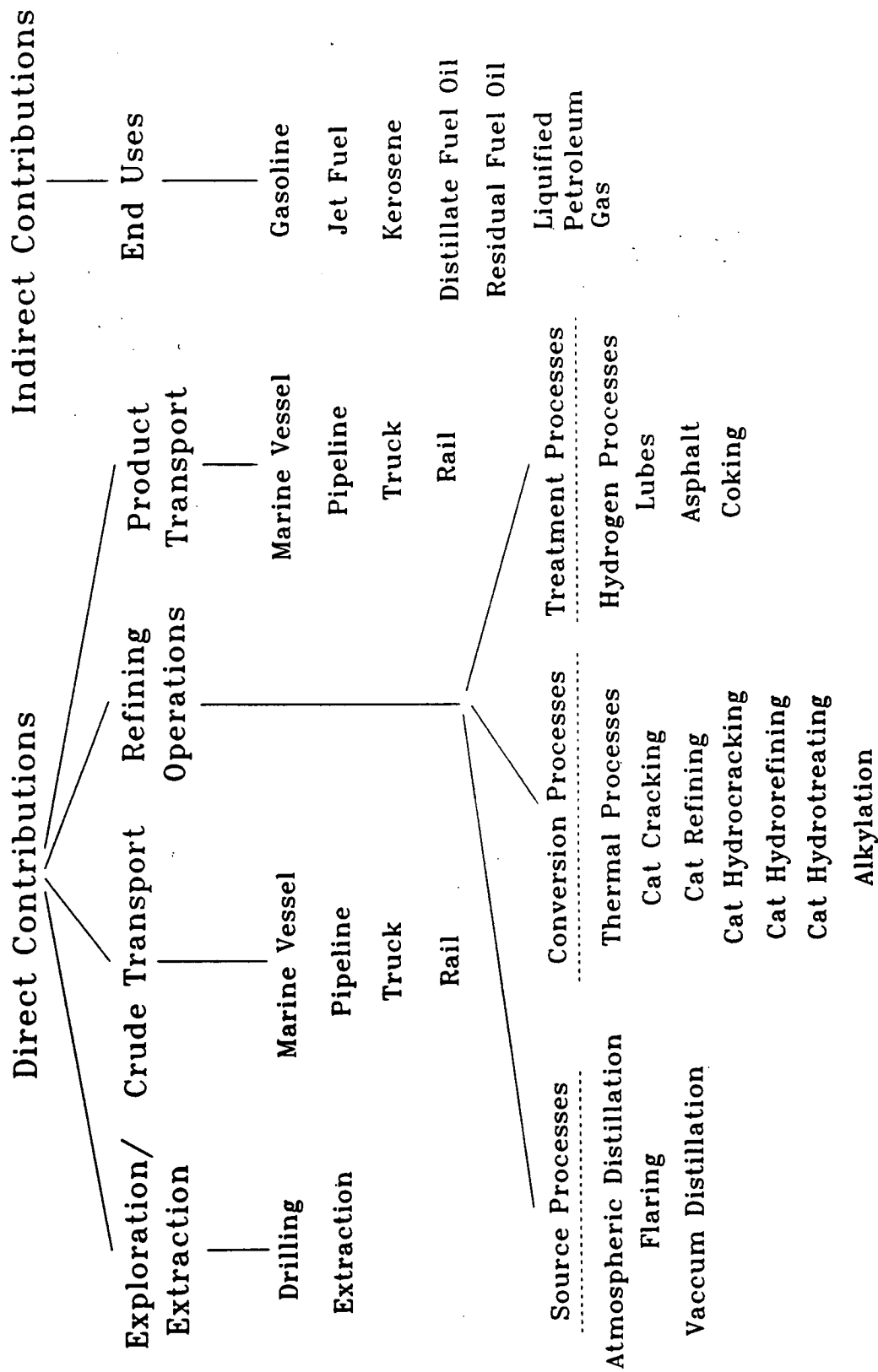


Figure 2-1. Petroleum industry segments contributing to global carbon dioxide emissions.

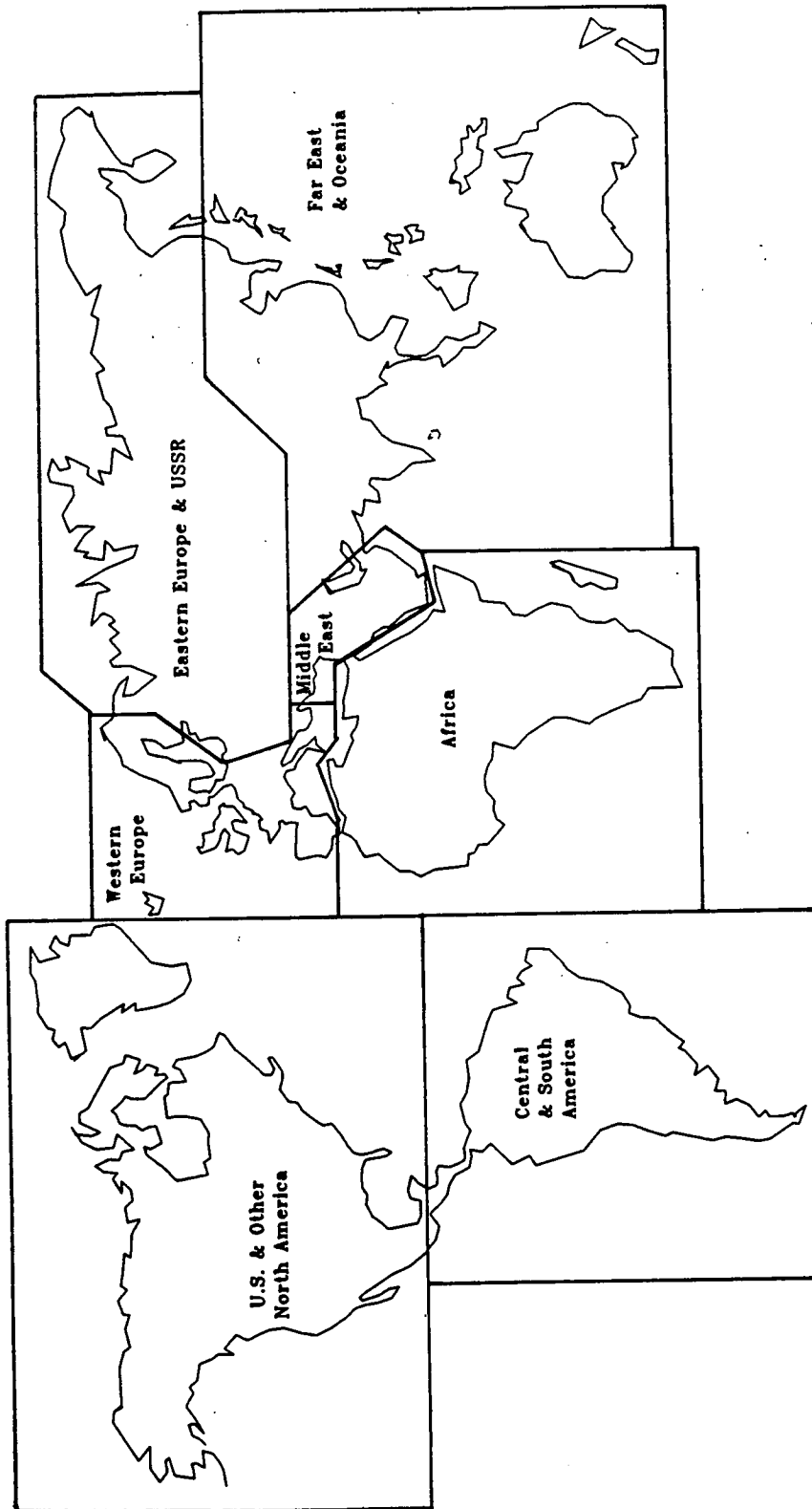


Figure 2-2. Geographic regions used in the CO₂ emissions inventory.

3.0 PETROLEUM INDUSTRY OVERVIEW

The definition of the petroleum industry used in this report encompasses all activities beginning with location of oil reservoirs through consumer use of petroleum products. The CO₂ emission estimates for this broadly defined industry have been divided into five major segments:

1. Exploration and Extraction,
2. Crude Petroleum Transportation to Refineries,
3. Refining Operations,
4. Refinery Products Transportation, and
5. End Uses.

Sources of CO₂ emissions were identified within each industry segment. In order to quantify emissions from each source, emissions were evaluated as a function of industry activity and rate at which the activity causes emissions. This rate is represented as an emission factor. For example, CO₂ emissions from well drilling are a function of the number of wells drilled and the amount of CO₂ emitted from a typical drilled well. In this case, the source of CO₂ emissions is well drilling, the activity level is the number of wells drilled, and the emission factor is the amount of CO₂ emissions per well site. Sources of emissions, activities, and emission factors for all industry segments are illustrated in Table 3-1.

TABLE 3-1. PETROLEUM INDUSTRY ACTIVITIES AND CO₂ EMISSION FACTORS

Major Category	Emission Source	Petroleum Activity	Emission Factor	Units of Emission Factor
Exploration/Extraction	Well prep. and drilling -prep. equipment -gas fired	Number of wells drilled Number of wells drilled	2887.4 0.03	tons CO ₂ /well drilled tons CO ₂ /well drilled
	Field prod. and proc. -processing equipment -gas flaring	Number of active wells Number of active wells	1.2 2.3	tons CO ₂ /active well/yr tons CO ₂ /active well/yr
Crude Transportation	Tank trucks	bbl mile	0.00001	tons CO ₂ /bbl mile
	Marine vessels	bbl mile	0.000001	tons CO ₂ /bbl mile
	Railcar	bbl mile	0.000006	tons CO ₂ /bbl mile
	Pipeline	bbl mile	0.000003	tons CO ₂ /bbl mile
Refinery Operations (heaters and boilers)	Atmospheric separation	bbl thruput	0.008	tons CO ₂ /bbl thruput
	Thermal processes	bbl thruput	0.08	tons CO ₂ /bbl thruput
	Catalytic reformation	bbl thruput	0.002	tons CO ₂ /bbl thruput
	Catalytic hydrotreating	bbl thruput	0.025	tons CO ₂ /bbl thruput
	Alkylation reactions	bbl thruput	0.03	tons CO ₂ /bbl thruput
	Hydrogen processes	bbl thruput	0.02	tons CO ₂ /bbl thruput
	Vacuum separation	bbl thruput	0.008	tons CO ₂ /bbl thruput
	Catalytic cracking	bbl thruput	0.008	tons CO ₂ /bbl thruput
	Catalytic hydrocracking	bbl thruput	0.02	tons CO ₂ /bbl thruput
	Catalytic hydrotreating	bbl thruput	0.006	tons CO ₂ /bbl thruput
	Aromatic/isomerization	bbl thruput	0.03	tons CO ₂ /bbl thruput
	Lubes	bbl thruput	0.01	tons CO ₂ /bbl thruput
	Asphalts	bbl thruput	0.006	tons CO ₂ /bbl thruput
	Cokes	bbl thruput	0.007	tons CO ₂ /bbl thruput
	Refinery flaring	bbl capacity	0.00004	tons CO ₂ /bbl capacity
Product Transportation	Tank trucks	bbl mile	0.00001	tons CO ₂ /bbl mile
	Marine vessels	bbl mile	0.000001	tons CO ₂ /bbl mile
	Railcar	bbl mile	0.000005	tons CO ₂ /bbl mile
	Pipeline	bbl mile	0.000003	tons CO ₂ /bbl mile
End Uses	Gasoline	bbl	0.4	tons CO ₂ /bbl
	Diesel (fuel oil No. 2)	bbl	0.5	tons CO ₂ /bbl
	Kerosene	bbl	0.5	tons CO ₂ /bbl
	Jet fuel	bbl	0.5	tons CO ₂ /bbl
	Residual fuel oil	bbl	0.5	tons CO ₂ /bbl
	Liquefied petroleum gas	bbl	0.3	tons CO ₂ /bbl

3.1 EXPLORATION AND EXTRACTION

Exploration and extraction activities include geological surveying and testing, exploratory and delineation drilling, and field drilling and production. Geological test methods are required to establish the presence of an oil reservoir. Typical survey and test methods for onshore and offshore wells include remote sensing (digital imagery and aerial photography), acoustic sounding (used for offshore wells), and seismic testing. Once the potential for oil development has been established in an area, exploratory drilling is employed to determine if sufficient resources exist to merit development. If the results of the exploratory drilling are satisfactory, delineation wells are drilled to determine the optimum locations for production wells. Delineation drilling starts shortly after exploratory drilling is completed.

The number of exploratory and delineation wells drilled in a reservoir is a function of the quantity of resources expected to be found in the area and the areal extent of the find. A larger find results in a greater number of wells; a smaller find warrants less exploratory activity. When exploration confirms the presence of sufficient quantities of oil to justify production, the field production and processing phase begins. Activities include the drilling of production wells and the installation of hardware (valve trees, pumps, etc.) necessary to bring the oil to the surface. For offshore production, platform construction and pipeline installation are also required.

Onshore and offshore field production requires drilling, which in its simplest terms involves cutting a hole in the earth's crust. Drilling is accomplished by using a rotary rig to turn a drill string and drill bit to break, dislodge, and fragment formation material. A drilling fluid (also known as a mud) is circulated down the string to the drill bit to cool and

lubricate the drill bits and to transport cuttings to the surface for disposal. Power for drilling is provided by diesel engines.

For offshore platform installation, the jacket and deck modules are fabricated onshore and towed to the offshore site. Once offshore, the jacket is sunk by one or more derrick barges and secured to the sea floor by pinnings. The deck section and components are then attached. The major emissions associated with platform installation are from the equipment on the derrick barges used to lift and secure the components and the tug boats used to tow the jacket modules to the platform.

The extraction stage of the production process involves the recovery of crude oil from the reservoir and the processing of the well stream for shipment to refiners. The two primary steps in this process are extraction and field processing.

Extraction is usually accomplished using one of four methods: natural flow, steam-flooding, natural gas injection, or thermal and chemical treatment. In natural flow extraction, natural reservoir pressure is sufficient to cause oil flow through the subsurface formation to the oil recovery well. However, natural flow wells often do not convey oil to the gathering system on the surface without some energy input from subsurface pumps or gas lifting systems. Gas lifting is accomplished by injecting natural gas into the downhole production tubing at various depths to assist oil flow to the surface. Natural flow recovery is also referred to as primary oil recovery.

Steam flooding and natural gas injection are used after natural flow recovery methods have failed. The use of these techniques is often referred to as secondary recovery. In secondary recovery, natural gas or steam is injected into the geological formation to induce the flow of crude oil to the collection system.

Thermal and chemical treatment methods are used after secondary recovery and are referred to as tertiary recovery or enhanced recovery techniques. Tertiary methods include in situ combustion, which heats the oil and reduces its viscosity, and surfactant injection, which reduces the ability of the formation to retain crude.

After the crude is extracted by one of these recovery methods, it is processed to remove water, solids, and gas that may be produced along with the oil. Water and solids removal is accomplished by allowing sufficient time for free water and solids to settle out and/or by chemically or electrically breaking oil-water emulsions. During this process, gas is also separated from the oil using a variety of processing units. The oil is then ready for shipment to refiners.

Carbon dioxide emissions associated with exploration and extraction can be divided into two categories: power generation and flaring. The primary source of CO₂ emissions during the exploratory phase are the large internal combustion engines that supply power for the drilling rigs. In addition, significant emissions can come from support vessels for offshore wells and earth moving and other heavy equipment in onshore operations. In most cases, the rig engines are diesel-powered. The heavy equipment used in both onshore and offshore operations normally burn diesel fuel. The support vessels for offshore exploration may also use diesel or fuel oil. Carbon dioxide emissions also occur as a result of flaring collected gases that are generated during exploration and extraction activities.

3.2 CRUDE TRANSPORTATION

The transportation of crude oil from field to refinery is, for the most part, accomplished by pipeline and marine tanker. A smaller portion of the crude is also transported by tank truck and railcar.

During transportation, CO₂ emissions result from the exhaust emissions of the vehicle engines. Carbon dioxide emissions from transportation vehicle engines is discussed in greater detail under the End Uses section. The generation of electric power necessary to operate the pipeline pumps creates the CO₂ emissions associated with pipeline transportation.

3.3 REFINING OPERATIONS

Refinery operations convert crude oil into multiple products with a variety of end uses. The scope of petroleum refining includes receiving the crude into storage and the refining operations. The petroleum refining industry employs a variety of processes for generating the desired products. The refining processes can be divided into three distinct categories: separation, conversion, and treatment. This section of the report presents an overview of these three categories.

3.3.1 Separation Processes

The first step in petroleum refining is separating crude oil into its common boiling point components. Crude oil consists of various hydrocarbon compounds including naphthenic, paraffinic, and aromatic hydrocarbons as well as such impurities as oxygen,

nitrogen, sulfur, and various metals. The separation process employs atmospheric and vacuum distillation techniques to separate common boiling point hydrocarbons.

Crude oil is heated in a process heater and then introduced to an atmospheric distillation column for separation of the lighter components. The topped crude drawn from the bottom of the atmospheric distillation column is reheated in the process heater and directed to a vacuum distillation column. Vacuum distillation occurs at a sub-atmospheric pressure allowing lower-temperature separation of the high boiling-point distillates associated with the petroleum crude. Further separations can occur to produce single-component products. The light ends of the atmospheric distillation (and conversion processes) are often further separated to recover $C_2/C_3/C_4$ compounds. These materials are sold as products or petro-chemical feedstocks. The aromatic fractions of the crude can be separated in a BTX process where benzene, toluene, and o-, m-, and p-xylene are recovered. Steam is often introduced to the distillation columns to enhance the recovery process.

The primary sources of CO_2 emissions from separation processes are associated with process heater and boiler exhausts, and from refinery flaring practices.

3.3.2 Conversion Processes

Once crude oil has been separated into common boiling point fractions, hydrocarbon molecules are converted into either larger- or smaller-size molecules. Large petroleum molecules are reduced to smaller molecules during thermal and catalytic cracking.

Cracking involves the decomposition and recombination of petroleum molecules primarily into motor fuels. Molecular structure is changed by a series of condensation reactions that result in the transfer of hydrogen atoms between molecules. The thermal cracking process exposes the hydrocarbon distillate to high temperatures for varying time periods to physically reorganize the distillate molecule. Thermal cracking has been largely displaced by catalytic cracking.

Catalytic cracking employs a metal catalyst to form high-octane gasoline. When distillate gas oil feedstock is passed through the catalyst, molecular recombination occurs rapidly, forming the smaller hydrocarbon molecules. Catalytic cracking is the most commonly used cracking process.

In other processing steps, small petroleum molecules are combined into larger molecules by polymerization and alkylation processes. Polymerization involves a reaction, generally carried out in the presence of a catalyst, where relatively simple molecules (monomers) are combined to form a molecule with a chain-like structure. The new chain-like molecules are referred to as polymers. Alkylation involves the introduction of an alkyl radical with a simple organic molecule. This reaction occurs in the presence of a catalyst to form a high-octane blending component for gasoline.

Molecular structure can be rearranged by isomerization and reformation processes to produce molecules with higher-value and greater utilization. Isomerization is a method of altering the arrangement of the atoms of a hydrocarbon molecule without changing the total number of atoms. Isomerization is generally used to convert straight-chain to branched-chain hydrocarbons or to convert aliphatic to aromatic hydrocarbons.

Most of the conversion processes require steam and/or heat to drive the chemical reactions. The primary sources of CO₂ emissions from these conversion processes include process heater and boiler exhausts and safety flare emissions.

3.3.3 Treatment Processes

The final step in the manufacture of petroleum products is process treatment. In this step, the petroleum products are stabilized and, in some cases, the product is separated from less desirable products to remove any contaminants. Typical treatment processes include hydrodesulfurization, hydrotreating, chemical sweetening, deasphalting, and acid gas removal. The overall purpose of treatment includes the improvement of color and odor; removal of sulfur compounds; removal of gums, resins, and asphaltic materials; improvement of stability in the presence of sunlight and air; and improvement of susceptibility to additives.

The CO₂ emission sources associated with treatment processes include process heater and boiler exhausts, and flaring losses.

3.4 PRODUCT TRANSPORTATION

Upon completion of the refining of petroleum products, the products are transported to various consumers and to petrochemical production facilities. The product transportation modes include pipeline, marine vessel, railcar, and tank truck. Carbon dioxide emissions occur from the combustion of distillate, diesel, and gasoline fuels required to operate the product carrier vehicles. Carbon dioxide is also emitted from the fuel combustion necessary to operate the pumps for pipeline transportation. This fuel

combustion can occur either on-site in engines used to operate the pipeline pumps or off-site in the generation of electric power to operate pipeline pumps.

3.5 END USES

There are three major categories of end uses for petroleum products that cause emissions of CO₂: transportation fuels, heating fuels, and fuels for electric power generation. A fourth end use category, chemical feedstocks, does not result in CO₂ emissions that can be attributed to the petroleum industry. The largest consumer of petroleum products is the transportation fuels segment, particularly motor vehicle gasoline. This section focuses on CO₂ emissions from the combustion of transportation fuel.

The quantity of CO₂ emitted is a function of the chemical characteristics of the fuel. Transportation fuels are used by various vehicles including automobiles, aircraft (both commercial and private), trucks, buses, trains, ships, and boats, with automobiles constituting the largest demand for motor gasoline. Gasoline-powered vehicle engines are internal combustion spark-ignition engines. These engines emit numerous combustion products including CO₂ as a result of the fuel combustion process.

Aircraft fuels include both naphtha-type and kerosene-type jet fuel and aviation gasoline. Aircraft engines include jet engines (turbofan, turbojet, and turboprop) and reciprocating piston engines. Diesel trucks, buses, and railroad locomotives are also major users of transportation fuels derived from petroleum. Nearly all of these vehicles are diesel fueled (some commercial trucks are gasoline powered, and a small percentage of trucks and buses are fueled with liquid propane gas).

Ships, barges, and other watercraft are powered by petroleum-derived fuels. The largest vessels such as tankers and freighters are fired with residual fuel oil. Steamships, the largest marine vessels, are powered by steam turbines, with steam generated by a coal- or oil-fired boilers. Other large marine vessels such as automobile or passenger ferries may be powered by large internal combustion (diesel) engines, and are called motor vessels. Smaller pleasure boats generally use motor gasoline or diesel fuel for their engines. Carbon dioxide is emitted from the fuel combustion in all the marine vessels identified above.

All petroleum fuel uses, including transportation, heating, and electric power generation, release their energy through the combustion process in either internal or external combustion devices or engines. The major product from petroleum combustion is CO₂, which is exhausted to the atmosphere.

4.0 PETROLEUM ACTIVITY DATA DEVELOPMENT

The five major segments of the petroleum industry discussed in Section 3.0, exploration/extraction, crude transport, refining, product transport, and end uses, were evaluated to estimate emissions of CO₂. Carbon dioxide emissions were calculated as a function of the level of activity within the respective petroleum industry segments. Examples include the number of wells drilled, the amount of oil transported by marine vessels, catalytic cracking throughput, and gasoline consumption.

The literature on the petroleum industry was thoroughly reviewed and petroleum industry statistics were gathered from several sources. All efforts were made to use the most recent available data. Data from 1989 were used to represent oil exploration/extraction and refining; data from 1987 through 1988 were used to represent crude and product transport and end use. Emissions estimates were calculated by developing a series of equations with the following form:

$$\text{CO}_2 \text{ Emissions} = \text{Activity Level} * \text{Emission Factor}$$

Emission sources, activity levels, and emission factors were presented in Table 3-1.

The databases used to develop global CO₂ emissions estimates from petroleum sources for this report vary in their level of accuracy and completeness. Every effort was made to obtain activity data for all major oil-producing and consuming countries. However, in some instances data for communist bloc countries were unavailable. The sources, development, and limitations of the activity data used to calculate global CO₂ emissions from petroleum industry sources are discussed in the following sections.

4.1 EXPLORATION AND EXTRACTION

To determine CO₂ emissions from exploration and extraction, two types of data were examined. First, the number of wells drilled each year was used to estimate CO₂ emissions from exploration. Second, the number of producing wells was used in determining emissions from extraction.

Carbon dioxide emissions from oil production and use include natural gas production in oil fields and all active oil and gas rigs associated with the exploration and extraction industry segment. Similar techniques are used to extract both crude oil and natural gas. Often natural gas and crude oil are produced from the same well. U.S. state and federal agencies in charge of counting oil and natural gas wells use different criteria for defining a co-producing well as oil producing or natural gas producing. For these reasons, it was not possible to separate data for oil wells from natural gas wells. However, it was possible to separate oil field data from gas field data. Therefore, data for total oil and gas well activity at oil fields were used to estimate production activities.

The Oil and Gas Journal International Rig Count [Oil and Gas Journal (OGJ), 1990a] was used as the source of the total number of wells drilled in 1989 on a country-by-country basis. The average rig operating in the United States in 1988 drilled 36.9 wells (Pennwell, 1990a).

$$34,579 \text{ wells drilled} / 936 \text{ active rotary rigs} = 36.9 \text{ wells per rig}$$

The U.S. average was applied to the international rig count to estimate the number of wells drilled in 1989 for each country throughout the world. Data describing the number of active rigs and exploration activities were not available for communist countries. This

approach overestimates the number of wells drilled in oil formations since the total number of wells drilled includes wells drilled in gas formations.

The number of currently producing wells that tap oil formations for each country was obtained from the OGJ Worldwide Field Production Survey (OGJ, 1989). The most recent available data from this survey were for 1988. Data for the United States, the Soviet Union, and China were not available from the survey. Data for these countries were obtained from the 1990 International Petroleum Encyclopedia (Pennwell, 1990b). Data for the remaining communist countries were not available. However, oil production from these countries is roughly one-half of 1 percent of global oil production (EIA, 1989).

4.2 CRUDE TRANSPORTATION

Activity data for the transportation of crude oil are reported in billions of barrel-miles. A barrel-mile is a unit representing the movement of one barrel the distance of 1 mile. Transport data were difficult to obtain, and assumptions about crude movements based on U.S. data were necessary. Four major modes of crude transport were examined: pipelines, marine vessels, trucks, and rail.

Barrel-miles of transport for each major mode of crude transport were available for the United States for 1987 (Sceath, 1989). The amount of crude oil used in the United States (barrels/day) in 1988 was also obtained (EIA, 1989). U.S. crude oil use was then applied to U.S. transport values to determine the amount of oil moved by each mode of transportation for each barrel of crude oil consumed per day. The U.S. ratio was applied to crude use in all other countries (EIA, 1989) to estimate crude movements by mode of transport.

This method was used to obtain the following global estimate for 1988: 8819.4 billion barrel-miles of crude were transported by pipeline, 9904.5 billion barrel-miles by marine vessel, 41.4 billion barrel-miles by truck, and 19.4 billion barrel-miles by rail.

4.3 REFINING OPERATIONS

Data for refining operations were summarized from the OGJ U.S. and Worldwide Refinery Surveys (OGJ, 1990b and 1990c, respectively). Activity data were aggregated by major production process group for each country. Production processes include atmospheric distillation, vacuum distillation, thermal processes, catalytic cracking, catalytic reforming, catalytic hydrocracking, catalytic hydrotreating, catalytic hydrorefining, catalytic hydrotreating, alkylation, aromatics/isomerization, hydrogen processes, lube production, asphalt production, and coke production.

These data were initially reported in terms of refinery unit capacity. An 87.9 percent capacity factor was applied to convert data from units of capacity to units of production. The capacity factor was calculated from U.S. refinery data (Pennwell, 1990a). Monthly capacity utilization rates were averaged for 1989 to determine the U.S. annual capacity utilization for 1989.

4.4 PRODUCT TRANSPORTATION

Data for the transportation of petroleum products are reported in billions of barrel-miles. The approach used to calculate product transport was similar to that used to calculate crude transport. Transport data were difficult to obtain, and assumptions were made about product movements based on U.S. data. The same four major modes of product transport were examined: pipelines, marine vessels, trucks, and rail.

Barrel-miles of transport for each of these modes were available for the United States for 1987 (Sceath, 1989). The amount of petroleum products used in the United States (barrels per day) in 1988 was obtained (EIA, 1989). U.S. petroleum product use was applied to the transport values to determine the amount of products moved by each transport mode for each barrel of product consumed per day in the United States. This ratio was applied to petroleum product use in all other countries to determine the product movement by transport mode (EIA, 1989).

These methods provided the following global estimates for 1988: 6957 billion barrel-miles of product were transported by pipeline, 4181 billion barrel-miles by marine vessel, 899 billion barrel-miles by truck, and 343.9 billion barrel-miles by rail.

4.5 END USES

The consumption of refined petroleum products for heat, power, transportation, and other fuel uses results in large emissions of CO₂. End use activity data for each country in the world for 1987 was obtained (EIA, 1989). Six major petroleum fuel products were examined: gasoline, kerosene, diesel fuel, jet fuel, residual oil, and liquified petroleum gas (LPG). Global consumption of these products is reported in Table 4-1.