AP42 Section:	1.1
Reference:	16
Title:	Carbon Dioxide Emissions from Fossil Fuels: A Procedure For Estimation and Results For 1951-1981, G. Marland and R. M. Rotty, DOE/NBB-0036 TR-003, Carbon Dioxide Research Division, Office of Energy Research, U.S. Department of Energy, Oak Ridge, TN, 1983.

June 1983

Prepared for:
United States Department of Energy

[redacted]OE/NBS-3
Dist. Category UC

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division
Washington, D.C. 20545

TR003

Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1981

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Under Contract No. DE-AC05-76OR00033

Major segments of the underlying analyses were completed u
Gas Research Institute Contract No. 5014-361-0202.

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EXECUTIVE SUMMARY

Measurements of atmospheric composition clearly demonstrate that the carbon dioxide concentration has increased by about 8 percent over the last 24 years (Keeling et al., 1982) and it is generally acknowledged that a major portion of the increase is related to the burning of fossil fuels. Although present in the atmosphere at only 338 parts per million (by volume), carbon dioxide absorbs infrared radiation in the wave lengths at which the earth radiates heat to space and experiments with general circulation models of the atmosphere indicate that a doubling of atmospheric CO_2 concentration would result in a rise in the mean earth surface temperature on the order of 2 to 3°C (see e.g., Manabe and Wetherald, 1980).

Because the growth in atmospheric CO_2 appears so closely tied to CO_2 emissions from fossil fuel burning and because the CO_2 issue has achieved considerable environmental significance, it seemed appropriate to review the analysis of Keeling (1973). The new data and revised methods attempt to reduce the uncertainties, and appear to make major modifications in the much used data set of CO_2 emissions from Rotty (1979, 1981) unnecessary.

The intent of this paper is thus two-fold: (1) to provide detailed documentation for a procedure to estimate CO_2 emissions from fossil fuels, and (2) to make independent and updated estimates of the rate at which fossil fuel combustion has released carbon dioxide in the atmosphere.

Carbon dioxide is an essential byproduct of fossil fuel burning, as seen in the equation

$$C_xH_y + (x + \frac{1}{4}y)\ O_2 \rightarrow x\ CO_2 + \frac{1}{2}\ y\ H_2O + \Delta H, \qquad \text{(Eq. 1)}$$

where ΔH is the heat of reaction and C_xH_y denotes a generalized hydrocarbon fuel. The calculation of CO_2 emissions is conceptually very simple. For each type of fuel, the annual global CO_2 emissions are the product of three terms: the amount of fuel produced, the fraction of the fuel that becomes oxidized, and a factor for the carbon content of the fuel. For CO_2 calculations, fossil fuels can conveniently be divided into the usual groups of gases, liquids, and solids. For each fuel group the annual fuel production (P) is multiplied by an estimate of the fraction of each year's fuel

production that is oxidized (FO) and by an estimate of the average carbon content of each fuel group (C) to give the CO_2 emissions for that fuel group. That is,

$$CO_{2_i} = (P_i)(FO_i)(C_i) \qquad \text{(Eq. 2)}$$

where subscript i indicates a particular fuel group and CO_2 is expressed in units of mass of carbon.

An important outcome of this exercise is that an independent examination of the full computation of CO_2 emissions from fossil fuels has not discovered any fundamental oversights in the earlier methods of Keeling and of Rotty. Differences from the earlier results are minor, well within the uncertainty limits in the data available. The values presented Table E-1 and displayed in Figure E-1 show graphically the rate at which CO_2 emissions have been growing and the relative contributions of the various fuels.The figure illustrates the early dominance of the emissions from coal and the rapid increase in emissions from liquids between 1950 and 1980. The disruption of the growth in emissions that accompanied the dramatic change in energy prices and availability beginning in 1973 is clearly evident and appears to be mostly a consequence of reduced growth rate in the use of oil and gas.

The percentages shown in Figure E-1 are average exponential growth rates calculated by linear least squares fitting of the logarithms of the annual emissions. Although the trends indicated for the period following 1973 are based on only nine points, and hence are susceptible to some adjustment as additional years are added to the data, the change in growth rates around 1973 is quite evident. The pre-1973 4.5 percent annual rate of growth in CO_2 emissions from all fossil fuels has been reduced to less than half that. Carbon dioxide emissions from oil and gas show the 1973 change even more clearly. The apparent small increase shown in the growth rate in coal production following 1973 must be considered in terms of the relatively short period over which the rate was determined.

TABLE E-1. CO_2 EMISSIONS FROM FOSSIL FUELS, 1950-1981 (10^6T C)

Year	Gas Fuel	Liquid Fuel	Solid Fuel	Flared Gas	Total From Fossil Fuels
1950	97	423	1,075	23	1,618
1951	115	478	1,135	24	1,752
1952	124	504	1,124	26	1,778
1953	131	534	1,130	27	1,822
1954	137	557	1,119	27	1,840
1955	150	625	1,212	30	2,017
1956	161	679	1,277	32	2,149
1957	178	714	1,314	35	2,241
1958	192	732	1,340	35	2,299
1959	214	790	1,375	36	2,415
1960	235	850	1,426	39	2,550
1961	253	906	1,337	41	2,537
1962	276	982	1,368	44	2,670
1963	300	1,054	1,426	47	2,827
1964	328	1,138	1,478	51	2,995
1965	351	1,220	1,500	55	3,126
1966	380	1,323	1,522	60	3,285
1967	409	1,422	1,464	66	3,361
1968	445	1,551	1,494	73	3,563
1969	487	1,669	1,522	80	3,758
1970	516	1,834	1,576	88	4,014
1971	553	1,945	1,572	90	4,160
1972	583	2,054	1,585	95	4,317
1973	608	2,238	1,604	112	4,562
1974	616	2,245	1,613	107	4,581
1975	621	2,130	1,683	96	4,530
1976	645	2,308	1,727	110	4,790
1977	662	2,401	1,765	108	4,936
1978	692	2,424	1,786	106	5,008
1979	730	2,525	1,886	105	5,246
1980	739	2,413	1,916	102	5,170
1981*	780	2,246	1,941	93	5,060

* 1981 values are estimates by authors based on partial year data.

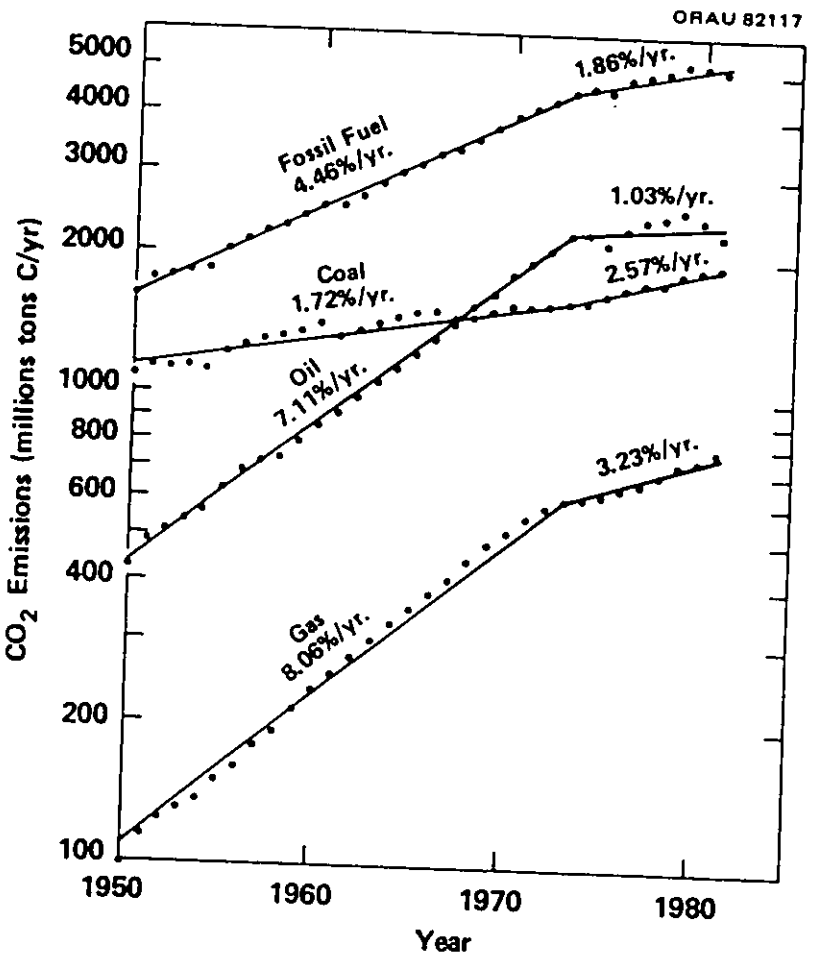

Figure E-1. Annual CO_2 Production from Each Fossil Fuel Group and Total Fossil Fuels.

This re-examination of procedures for calculation of CO_2 emissions had an additional result: estimates of the uncertainties in the final numbers. Because of the nature of the data used it has been impossible to quanitatively determine uncertainties and the authors have been left to estimate uncertainties based on subjective judgments of their own and of others who have worked with the data. In virtually all cases numbers have been closely bounded so that absolute errors cannot be large and errors in the time trends are even smaller. The largest absolute uncertainty enters the computation with the United Nations data set for fuel production but even here global fuel production is dominated by a small number of countries, most of which are believed to maintain and publish good statistical records.

Although the estimated uncertainty in the CO_2 emissions is about 10 percent, the trend of increasing emissions from fossil fuels is firmly established. There may be a small time-dependent error in the emissions calculation but the 1950-1973 annual growth rate cannot be far from the 4.5 percent per year calculated here and, although not yet well defined, it is clear that the long-term growth rate following 1973 is about half the earlier rate.

The development of the data set for CO_2 emissions depends on the three factors; fuel produced, fraction oxidized, and carbon content of the fuel, as indicated above. The calculations rely heavily on United Nations data for world fuel production. Global fuel production numbers published by the United Nations are consistent with numbers published elsewhere and represent the best efforts of a staff dedicated to the sole task of bringing together all of the available information. Fuel production data for any year are subject to revision as additional information becomes available but ultimately all data depend on the reporting of individual nations and production companies. The UN does present most of its data in energy rather than mass units, a great asset since there is a wide range of resource quality and hence composition. For each fuel type composition can be correlated with heating value.

For utility in calculating CO_2 emissions, fuel production numbers must be carefully defined. The quantity of interest for natural gas production is, for example, what the U.S. Department of Energy would identify as "marketed production" minus "extraction loss." Reinjected gas is not counted,

flared gas is treated separately, and gas liquids are grouped with liquid fuels. Hence the "extraction loss" in gas processing is essentially a transfer to the liquid accounts. For liquid fuel production the simple sum of mass of crude oil and natural gas liquids is used because the carbon content is approximately the same for the two categories of liquid fuels. For coal, the UN has defined a "ton of coal equivalent" essentially as 29.31×10^9 joules and all coal has been adjusted for quality and compiled on this basis. Some confusion is created by the most recent UN publication relying on an unconventional definition of heating value for coal, but the intent is clear and calculations here compensate with a correction factor included in the carbon content term. The use of these units for the fuel produced determines the form, and to some extent the value, of the term used for carbon content.

Global data on flaring of natural gas have been published by official agencies only for 1971-1978 and even these are "partly estimated." These data from the U.S. Departments of Interior and Energy have been supplemented with the authors' estimates and by earlier published values of Rotty (1974). While these values are subject to considerable uncertainty (estimated at ±20 percent), they comprise only about 2 percent of the total CO_2 emissions.

Throughout this exercise it is clear that CO_2 emissions occur at fossil fuel use, not production, but that calculations are based on production. On an annual basis, however, production data can serve adequately if compensation is made for the uses of the material which do not result in oxidation of carbon--i.e., nonfuel use such as petrochemical feedstocks and asphalt, and in fuel use through losses to the environment and inefficiencies of combustion. Although either approach could be chosen, because production data are better and more straightforward than consumption data, this is the approach taken here. This choice requires that the terms for the fraction oxidized include consideration of both nonfuel use and incomplete combustion. Because the U.S. role in world fuel production has been so dominant (44 percent of total fossil fuel production in 1950, 22 percent in 1980) details of U.S. fuel use can provide a reasonable guide to global patterns for nonfuel use as well as for efficiency of combustion. Information on the breakdown of use of fuel material for nonfuel use is very limited for many

parts of the world and therefore the procedures developed and used here start with a U.S. pattern and are adapted as seems appropriate to the global scale.

Selection of factors for fraction oxidized (FO) requires some effort to acknowledge that fuel which is produced but not oxidized this year will nonetheless be oxidized over a period of some years, the rate dependent on how the material is used and ultimately disposed of. It is estimated here that the quantity of natural gas oxidized in any year, including continuing oxidation of products from previous years, is equivalent to 98 percent of current year production; for liquid and solid fuels this factor is 91.8 percent and 98.2 percent respectively. The smaller number for liquid fuels is because of wide usage for paving materials, plastics, synthetic fibers, lubricants, etc. The uncertainty adopted for nonfuel use of liquids (ranging from 4.7 to 8.7 percent) is near a factor of two, but the uncertainty imposed on the subsequent calculation of CO_2 emissions is only ±2 percent. The fraction oxidized has probably been changing with time, and this could introduce uncertainty. The efficiency of fuel burning has almost certainly been increasing, resulting in a small overestimation of CO_2 in the early years. However, the nonfuel use of fuels has probably been increasing and the time-dependent bias in the trend of CO_2 emissions numbers from this effect is opposite to that of improved combustion.

There is no systematic tabulation of the carbon content of fuel produced all over the world, but having fuel production numbers in energy units makes it straightforward to estimate carbon content. Analysis of a broad sampling of world analytical data and conversion to units compatible with UN fuel production numbers gives the following factors for the mean carbon content of fuels: gases, 13.7 tons C per 10^{12} joules (510 g/m^3); liquids, 0.85 tons C per ton fuel; and solids, 0.746 tons C per ton coal equivalent. The factor for coal is uniquely appropriate for use with UN tabulated values for tons of coal equivalent (defined for "net heat value"). The factor includes an adjustment to make the UN definition of heating value compatible with coal compositional data available from other sources.

Estimates of uncertainty in these calculations are highly subjective, and appreciation of this fact is essential. Full understanding of the increase in atmospheric CO_2 requires that historical data of CO_2 emissions be used along with data describing other portions of the carbon cycle.

Some measure of uncertainty is important and the authors attempt to increase the value of the results by providing 90 percent confidence limits on the calculated emissions. This effort is summarized in Table E-2. As indicated in the Table each annual total presented in Table E-1 is estimated to have an uncertainty of between 6 and 10 percent. However, because data from successive years are highly correlated, the year-to-year changes are probably known with much greater accuracy than the individual annual values.

TABLE E-2. UNCERTAINTIES IN CO_2 EMISSIONS (%)

	E_1 Fuel Produced (P)	E_2 Fraction Oxidized (FO)	E_3 Carbon Content (C)	Emissions* $\sqrt{\Sigma E_j^2}$	Weighted** Emissions $f_i \sqrt{\Sigma E_j^2}$
Gases	10	1	2	10.25	1.47
Liquids	8	3	1	8.60	4.01
Solids	11.2	2	2	11.55	4.28
Gas Flared	20	1	3	20.25	0.41

Total Uncertainty:

a. If uncertainties for the individual fuels are mutually independent. $\left[\sum_i \left(f_i \sqrt{\Sigma E_j^2}\right)^2\right] = 6.06$

b. If uncertainties for the individual fuels are not independent. $\sum_i f_i \sqrt{\Sigma E_j^2} = 10.16$

* E_j is the uncertainty in the factors P, FO, and C for a given fuel type i.

** Weighted by 1980 weighting factor f_i = 1980 emissions from i th fuel type divided by total 1980 emissions.

THE PROBLEM

In attempting to identify the possible causes and consequences of the observed increasing atmospheric CO_2 concentration, the source of the CO_2 is a major concern. Through the past several decades, the combustion of fossil fuels has grown immensely and it is clearly an important source of CO_2.

The intent of this study was two-fold: (1) to provide detailed documentation for a procedure to estimate CO_2 emissions from fossil fuels, and (2) to make independent and updated estimates of the rate at which fossil fuel combustion has released carbon dioxide to the atmosphere. The CO_2 issue has achieved such significance that it is appropriate to review the analysis of Keeling (1973) and affirm that the much used data sets of CO_2 emissions from Rotty (1979, 1981), using Keeling's procedure, do not contain significant oversights. This work is intended to provide independent and updated estimates of CO_2 emissions and undue significance should not be attached to minor differences from previously published values.

The result of the calculations described here will be a table which displays, for the period 1950 through 1981, the amount of fossil fuel produced and the amount of CO_2 discharged to the atmosphere as a consequence. A final graph will display, for each fuel and for the global total, how CO_2 emissions have varied as a function of time.

RATIONALE

The calculation of CO_2 emissions from fossil fuels is conceptually very simple. For each type of fuel, the annual CO_2 emissions are the product of three terms: the amount of fuel produced, the fraction of the fuel that becomes oxidized, and a factor for the carbon content of the fuel. For CO_2 calculations, fossil fuels can conveniently be divided into the usual groups of gases, liquids, and solids. For each fuel group we start with annual fuel production data(P). Multiplying P by the fraction of each year's fuel production that is oxidized (FO) and by the average carbon content of each fuel group (C) will give the CO_2 emissions for that fuel group. That is,

$$CO_{2_i} = (P_i)(FO_i)(C_i) \qquad \text{Eq. 1}$$

where subscript i indicates a particular fuel group and CO_{2_i} is expressed in mass of carbon.

The data for annual fuel production must recognize that all coal (or natural gas or crude oil) is not of the same composition, and thus may have varying energy content and CO_2 potential. It is easiest to accomplish this by using fuel production data in either energy or energy equivalent units (for example, tons of coal equivalent).

The second factor in Equation 1, the fraction becoming oxidized, requires examining the use of fuels. For coal, nearly all the production at present is for combustion, and the effectiveness of the combustion process determines the fraction of the carbon that is oxidized. For liquids and gases we must account not only for inefficient combustion but also for nonfuel uses. Derivation of this factor for each fuel group is based on data for the products of petroleum refineries and natural gas processing plants.

There is no systematic tabulation of data on the carbon content of fuel produced all over the world. For liquid fuels and for natural gas the hydrogen-carbon ratio largely determines the heating value and for solid fuels most of the combustion energy is from oxidation of carbon. Thus for

each fuel the heating value is closely correlated to the carbon content and the energy equivalence concept used in the tabulation of production data makes it possible to deduce fuel composition quite accurately.

The final term in Equation 1 is a factor which relates carbon content to energy content for each fuel group. The complete combustion of a fossil fuel can be represented by

$$C_x H_y + (x + \frac{1}{4} y)\ O_2 \rightarrow x\ CO_2 + \frac{1}{2} y\ H_2O(gas) + \Delta H_L$$

or

$$C_x H_y + (x + \frac{1}{4} y)\ O_2 \rightarrow x\ CO_2 + \frac{1}{2} y\ H_2O(liquid) + \Delta H_H$$

where ΔH is the heat of reaction and C_xH_y denotes a generalized fuel. For combustion of hydrocarbons the heat of reaction is negative in the thermodynamic sense, meaning that heat is given off. When all the water in the products of combustion is liquid (for combustion at relatively low temperature) the higher (or gross) heating value, ΔH_H, is appropriate. ΔH_H is always greater than the lower (or net) heating value ΔH_L because of the energy required in the vaporization of water. Real fuels vary considerably in composition--both in time and place--hence x and y are different not only for average natural gas and petroleum, and for different petroleum products (gasoline vs. fuel oil), but also for crude oil from different fields. This makes development and use of global averages very important and is accomplished by using the energy equivalence basis, i.e. the implicit relations between ΔH and x and y.

In the past, CO_2 emissions have often been based on United Nations fuel production data using similar procedures (described by Keeling [1973] and Rotty [1973]). During the past decade the United Nations statistical office has modified their reporting toward a more consistent fuel equivalence basis. This has necessitated modifications in the procedures for calculating CO_2 emissions to assure consistency. Most recently, Rotty (1982)

calculated the global emissions from fossil fuel for the years 1950-1979 and estimated 1980 emissions from incomplete data. In the final section of this report is an updated version of these emissions computations and an estimate for 1981.

FUEL PRODUCTION DATA

In approaching calculations of carbon dioxide emissions it is useful to begin by examining the first term on the right in Equation 1. A consistent set of global fuel data is clearly required and the form of the other two factors will be dictated by the definitions and accounting units used in the fuel production data.

Most investigators calculating the production of carbon dioxide from fossil fuels have relied on data published by the United Nations. The U.S. Bureau of Mines, the Energy Information Administration of the U.S. Department of Energy, the World Bank, the Organization for Economic Cooperation and Development, and numerous other national and international organizations also maintain data on fuel use and energy activities. The UN Statistical Office energy unit offers the most complete and consistent time series for global fossil fuel production and consumption, partly because information from the other sources is used in the development of the UN data, but most important because the UN data set is continually modified and updated. The reliability of the data (and the suitability of its use in CO_2 calculations) has consistently improved through the years as more information has become available to the UN staff and as energy information has become more important in world activities.

Although the United Nations data are now in relatively consistent energy or energy-equivalent units, the nature of our computations and common usage in the various disciplines insure that a mixture of units of measure are encountered. Despite the potential for confusion with mixed units, we believe it important to distinguish between data taken from other sources and data which have been manipulated by us. Most data are thus presented in the units of the initial compilation and any manipulations requiring, for example, mass to volume or mass to energy-content conversions are carefully documented. Throughout this document "tons" should be understood to be metric tons.

Production of Natural Gas

Although we are interested in global data, the pattern for gas production and distribution in the U.S. is useful to help understand terms and

processes. Figure 1 has been prepared from data published by the Energy Information Agency of the U.S. Department of Energy and shows the 1980 flows of natural gas in the United States. In calculating the CO_2 emissions we must account for all the gas that is withdrawn from wells and becomes oxidized. Gas reinjected into the earth to repressure oil wells should not be counted and we will account separately for gas vented and flared. Hence "marketed production" is our starting point. The tabulations illustrated in Figure 1 permit accounting for the loss of gas volume during processing for recovery of liquids ("extraction loss"). The systematic approach of combining liquids extracted from natural gas with other liquid fuels has been adopted here. To avoid counting this quantity twice the basic number we must consider in our analysis of CO_2 emissions from gas is the marketed production minus the extraction loss. In fact, this is the number now recorded by the UN Statistical Office as natural gas production. The UN Statistical Office reports this natural gas production for all the producing countries.

Of course all of the gas produced in a given year is not necessarily consumed in the same year. One reason for this is net changes in storage, but the numbers shown as "to storage" and "from storage" in Figure 1 show that for 1980 the error on this account is less than 1 percent in the U.S. Over periods of very few years the changes in storage will tend to balance and global totals of imports and exports should also balance. Figure 1 suggests another issue which cannot be neglected by balancing over a few years or integrating over the whole globe. Some fraction of the industrial-use gas is for non-fuel uses and will be oxidized over time periods ranging from essentially immediate to decades. These uses include, for example, ammonia and methyl alcohol production and a variety of other petrochemical feedstock requirements. In the following section we will make allowance for the fraction of fuels produced but not oxidized.

In their early fuel data the UN tabulated natural gas production in cubic meters, counting gases with widely varying compositions on the same basis. Natural gas data were later changed to reflect the energy content of the gas and were tabulated in teracalories. Beginning with the publication of the 1979 Yearbook of World Energy Statistics the data are given in terajoules. The UN has converted all the published gas data (i.e., back to 1950) to the terajoule basis. Because the carbon content is closely

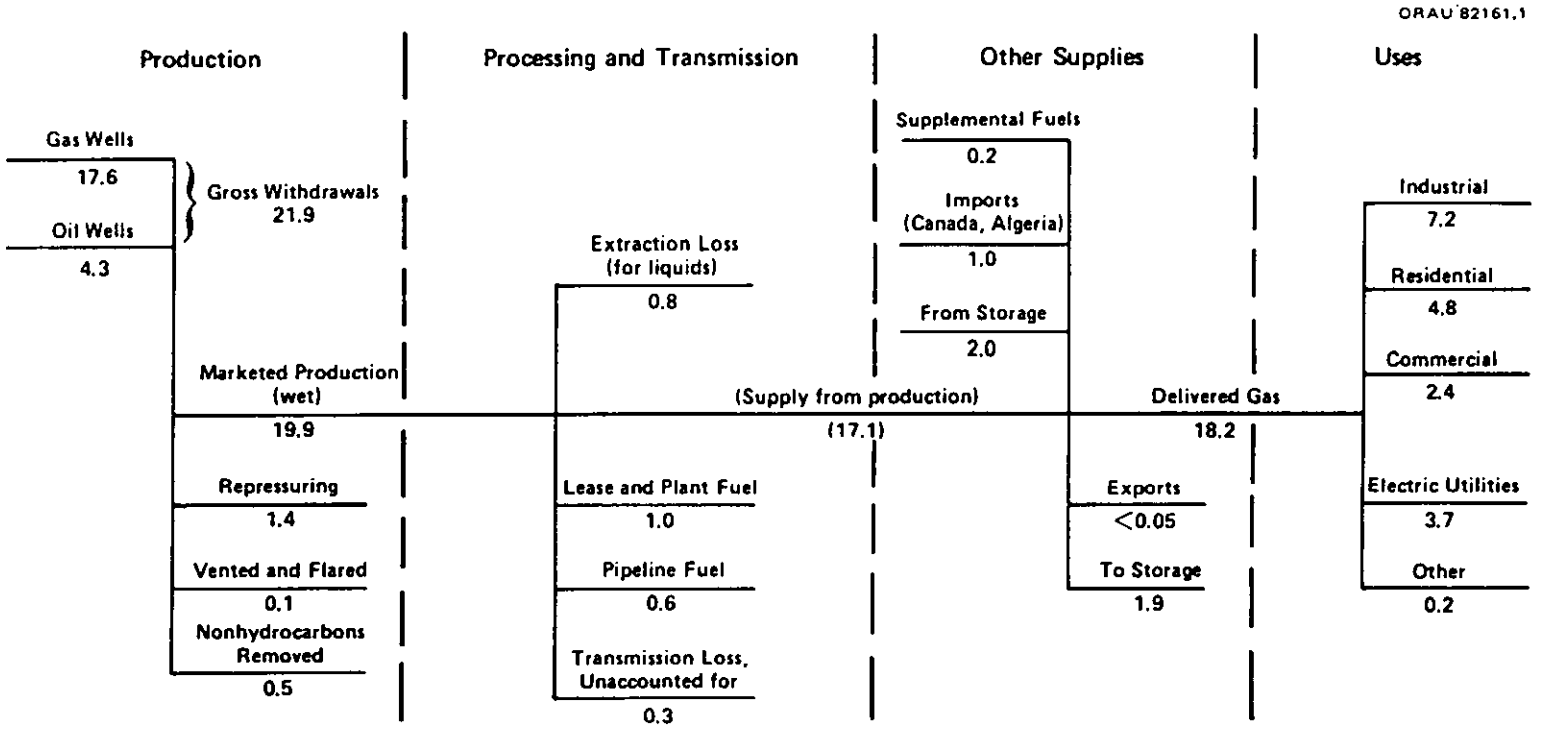

Figure 1. U.S. Flows of Natural Gas, 1980 (in 10^{12} cubic feet; $1 ft^3 \approx 0.028317 m^3$)
Data from *Natural Gas Annual, 1980,* U.S. DOE, (1982a).

correlated with the heating value of the gas, we believe that this has improved the estimates of CO_2 emissions from natural gases.

Many of the UN data sets for natural gas are received in the statistical office in energy units. That is, in response to the UN questionnaires, the individual countries (or organizations acting on behalf of individual countries) submit natural gas data in terms of the energy content of the gas. The UN maintains a reference table of heating values for gas from each country, but it must be pointed out that these values are not usually used in making volume to energy conversions in the UN office. Although it is not always clear, most of these values are as reported by the individual countries, and most appear to be based on higher heating values of the fuel. We will use these conversion factors to characterize the carbon content of natural gas. The most recently revised UN data for natural gas production during the period 1950-80, are given in our summary Table 14, column 1. Because the gas industry has been so tightly regulated, recent gas production numbers for the U.S. are likely to be correct within ± 5 percent. Non-U.S. production numbers are less accurate but we suggest that the figures for annual global totals are within ± 10 percent. Our confidence in the global figures is enhanced by recognition that the quality of the data should be improving with time, and the historic data are heavily dominated by U.S. production. It was in 1974 that U.S. production first dropped below 50 percent of the world total and as recently as 1960 U.S. production of natural gas exceeded 75 percent of the world total.

Production of Liquid Fuels

As in the case of natural gas, the global production and use of liquid fuels can be viewed through the analog of the detailed flow of liquid fuels for the United States. Based on data from the Energy Information Administration of the U.S. Department of Energy, the 1981 mix and flow of liquid fuels in the U.S. can be depicted as in Figure 2. Note that liquids derived from natural gas are treated here as a separate production source.

Just as with natural gas, imports and exports do not have to be considered if CO_2 emissions are based on global fuel production. However, if interest is on the distribution of CO_2 emissions among countries (or parts

of the world), different procedures must be considered. The distribution based on consumption will be drastically different from the distribution based on production, because such a large fraction of the crude petroleum produced is involved in international trade. On the other hand, because the net change in stocks is a small number, using total production numbers to indicate total consumption and CO_2 emissions introduces negligible error.

As indicated in Figure 2, most of the liquids are used as fuels and hence oxidized within a relatively short time of production. However, the use of production data for liquid fuels in computing CO_2 requires a correction for the liquids that are not oxidized in their use. Nonfuel uses of petroleum liquids come primarily under the "other" category in the last column of Figure 2 and it is here that major adjustments will be made.

The United Nations combines U.S. Department of Energy statistics with official or unofficial tabulations from other nations to arrive at world production statistics for crude petroleum and for natural gas liquids. As in the case of natural gas, the UN data are taken to be the best available for our purposes because of their completeness, historical consistency, and clear conformity with other available data. The UN production data for liquids, like those for other fuel types, are widely quoted by others and are essentially identical to "independent" values published elsewhere (see, for example, Table 1). The agreement of the UN data with data published by other organizations does not imply that the data are accurate to a limit described by these variances. Frequently the primary sources are identical, and some of the differences are due to interpretations and assumptions about standards.

In considering sources of error in the data on liquid fuels, an area of concern is the handling of natural gas liquids. These liquids comprise a mixture of compounds, some of which are used directly as fuel or chemical feedstocks and some of which are combined with crude petroleum or its intermediate products in refineries. On the average, natural gas liquids (NGLs) have a lower carbon-to-hydrogen ratio than crude petroleum, and thus, on a per unit mass basis, a higher energy content. Because the UN data on liquid fuels are designed to be representative of the energy content of the fuel, their liquid fuel data set (on an energy equivalent basis) is compiled by multiplying NGLs by 1.06052 and then adding to the crude petroleum

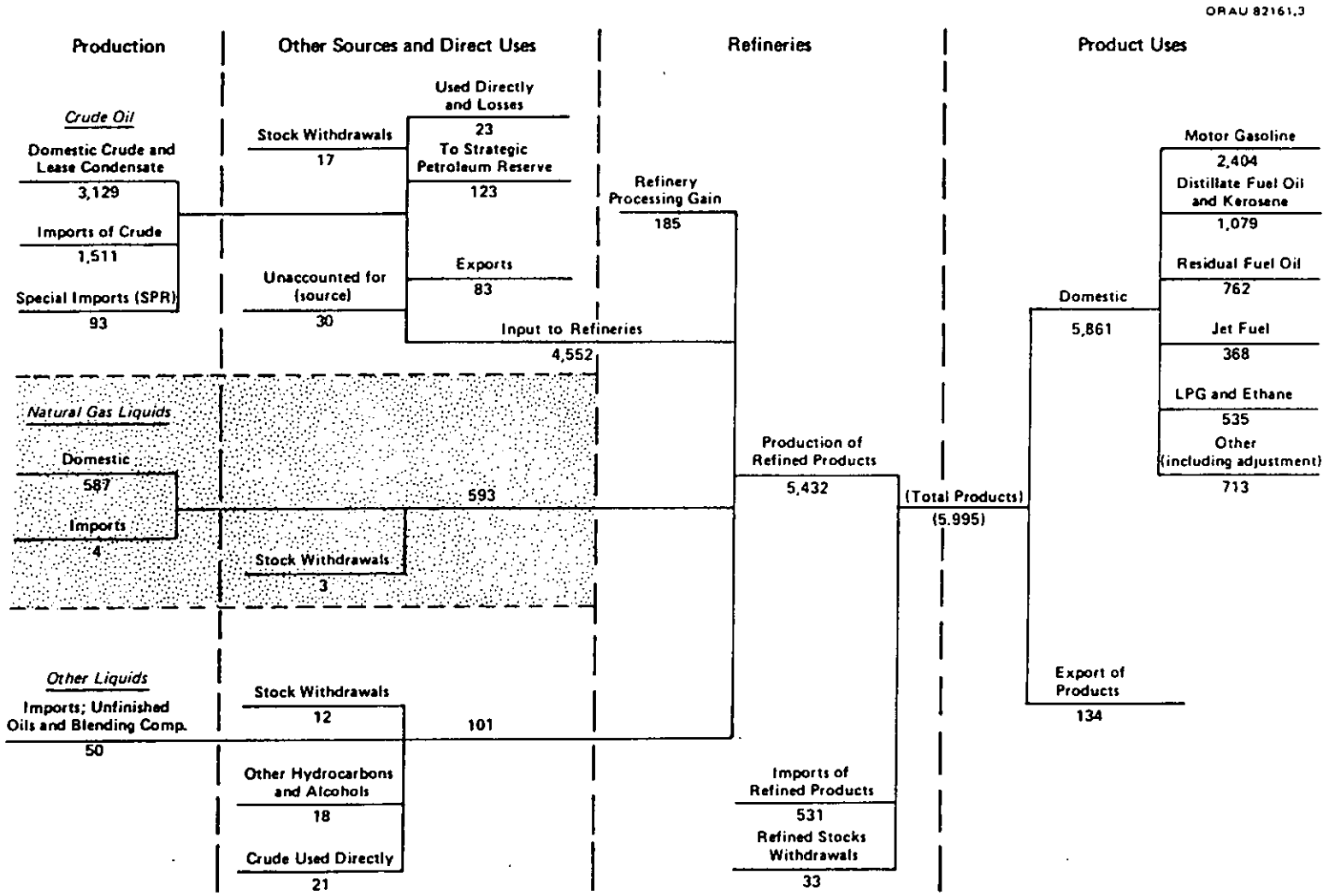

Figure 2. U.S. Flows of Liquid Fuels, 1981 (millions of barrels; 1 barrel ≈ 0.135 tons)
Data from *Petroleum Supply Annual, 1981*, DOE/EIA-0340 (81)/1, (1982b).

TABLE 1. WORLD CRUDE OIL PRODUCTION AS REPORTED BY DIFFERENT SOURCES* (10^6 tons oil equivalent)

	1980 Yearbook of World Energy Statistics (a)	Enright, Vielvoye & Beck (b)	U.S. CIA (c)	API (d)
1980	2,986	2,974	2,974	
1979	3,127	3,122	3,134	
1978	3,012	3,011	3,011	3,033
1977	2,985	2,982	2,987	2,998
1976	2,870	2,872		2,901
1975	2,644	2,651		2,669
1974	2,789	2,795		2,811
1973	2,780	2,793		2,788
1972	2,548	2,514		2,546
1971	2,413	2,394		2,418
1970	2,275	2,266		2,288

(a) 1980 Yearbook of World Energy Statistics, U.N., (1982), and Data Tape of UN Energy Statistics, Carbon Dioxide Information Center, Oak Ridge National Laboratory.
(b) From Enright, Vielvoye, and Beck (1981).
(c) From U.S. Central Intelligence Agency (1981).
(d) From American Petroleum Institute (1981).
* All data (except UN) were reported in barrels or barrels per day and were converted to tons oil equivalent by assuming a mean gravity of 32.5° API.

production. The factor 1.06052 is the correction factor to reflect that the NGLs have a 6.052 percent greater heating value per unit of mass than average crude petroleum.

For the purpose of calculating CO_2 emissions, we do not wish to employ this weighting factor introduced to account for more hydrogen in the fuel, so have adopted the procedure of simply adding the mass of natural gas liquids to the mass of crude petroleum. On the assumption that crude petroleum contains 85 percent carbon (see discussion below regarding carbon content of crude petroleum) and that NGLs contain between 80 and 84 percent carbon (C_2H_6 is 80 percent carbon, C_7H_{16} is 84 percent carbon), the error in considering the combination as all crude is very small. For the world as a whole, the mass of NGLs is about 3 percent of the mass of crude petroleum production. The carbon fraction for the mixture should be about

$$(0.97)(0.85) + (0.03)(0.82) = 0.8491,$$

which is so close to the carbon fraction of crude petroleum as to make any error from the combination procedure negligible. However, in the future, as more liquids are captured from natural gas and as the mixture of natural gas liquids shifts toward lighter compounds, consideration might be given to revising the procedure of simply adding data for NGLs to data for crude production. At present the most appropriate liquid fuel data for our purpose are obtained by adding the UN data for mass of crude petroleum to the UN data for mass of natural gas liquids. The result for world liquid fuel production is given in column 3 of the summary table (Table 14).

The global accounts for world production of liquid fuels consist of data for many parts of the world. In some cases these data appear to be highly reliable, e.g. OECD nations, but in others where smaller resources are committed to documentation, the data are less reliable. The UN staff has attempted to evaluate the reports and make appropriate adjustments when evidence warrants, but quantifying the reliability is impossible. Because most of the crude oil is produced in a relatively few countries and because the value of each unit of oil has become so high, we believe that since 1974 the world oil accounts involve uncertainty that does not exceed some ±8 percent, and would be better if data from Iran and Iraq were more reliable. Before the higher prices and more careful accounting resulting from the 1973-74 embargo, the uncertainty could have been more, but at that time the

data from Iran were much better than now, and the data from the U.S.A., U.S.S.R., and Saudi Arabia have probably been consistently reliable. Information now available is inadequate to allow formal calculations of uncertainties for global petroleum production. We estimate the data for the period before 1974 to contain an uncertainty of ±10 percent.

Production of Solid Fuels

Coal is an immensely variable commodity; both its heating value and carbon content vary over wide ranges. The ASTM scheme for classification of coals by rank (Table 2) makes it clear that tons of "coal" is not a fully adequate value for establishing how much carbon is likely to be released during burning. We need, in addition, some indication of the quality of the coal and this is basically what the UN Statistical Office has tried to achieve in reporting tons of coal equivalent. The UN basis for coal equivalency comprises 7000 calories per gram (29.31×10^9 joules/ton).

Adopting United Nations data for coal production subsumes most of the questions about coal quality in the coal production numbers. When the UN reports coal production in units of tons of coal equivalent, they have already made the conversion, in energy-equivalent units, from a ton of, say New Zealand brown coal, to tons of coal equivalent. We consider how well the UN standard of 7000 cal/g represents average coal.

That 7000 cal/g is an appropriate base for coal equivalents is supported by the compilaton of Zubovic et al. (1979), who summarized analytical data on 617 bituminous coal samples from the eastern U.S. The arithmetic mean heating value came out to be 7090 cal/g (12,670 Btu/lb), the geometric mean heating value 6996 cal/g (12,590 Btu/lb). An earlier study by Swanson et al. (1976) led to a mean heating value at 6812 cal/g (12,260 Btu/lb) for 277 bituminous coal samples. The U.S. Bureau of Mines has consistently used a heating value of 7057 cal/g (12,700 Btu/lb) for anthracite.

U.S. Bureau of Mines and U.S. Department of Energy data show the decreasing higher heating value of bituminous coal and lignite produced in the U.S. (Table 3). The U.S. value has been below 7000 cal/g since 1967 as the electric utility industry has increased use of western coals with

TABLE 2. CLASSIFICATION OF U.S. COALS BY RANK

Class	Group	Fixed Carbon Limits, % (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, % (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu/lb* (Moist, Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	
I. Anthracitic	1. Meta-anthracite	98	—	—	2	—	—	Nonagglomerating
	2. Anthracite	92	98	2	8	—	—	
	3. Semianthracite	86	92	8	14	—	—	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	—	—	Commonly agglomerating
	2. Medium volatile bituminous coal	69	78	22	31	—	—	
	3. High volatile A bituminous coal	—	69	31	—	14,000	—	
	4. High volatile B bituminous coal	—	—	—	—	13,000	14,000	
	5. High volatile C bituminous coal	—	—	—	—	11,500	13,000	
						10,500	11,500	Agglomerating
III. Subbituminous	1. Subbituminous A coal	—	—	—	—	10,500	11,500	Nonagglomerating
	2. Subbituminous B coal	—	—	—	—	9,500	10,500	
	3. Subbituminous C coal	—	—	—	—	8,300	9,500	
IV. Lignitic	1. Lignite A	—	—	—	—	6,300	8,300	
	2. Lignite B	—	—	—	—	—	6,300	

From: ASTM (1974).

* 12,600 Btu/lb = 7,000 cal/gm = 29.31×10^9 joules/ton.

TABLE 3. DECREASING HEATING VALUE OF PRODUCED U.S. COAL

	Higher (gross) heating value[a] (cal/g)		Lower (Net) heating value[b] (cal/g)	
1980		(6,292)[c]	5,860	(5,977)[c]
1979	6,234	(6,284)[c]	5,860	(5,970)[c]
1878	6,234	(6,395)[c]	5,880	(6,075)[c]
1977	6,307		5,910	
1976	6,428		6,110	
1975	6,446		6,120	
1974	6,589		6,260	
1973	6,669		6,340	
1972	6,682		6,350	
1971	6,734		6,400	
1970	6,829		6,490	
1969	6,918		6,570	
1968	6,962		6,610	
1967	6,990		6,640	
1966	7,029		6,680	
1965	7,062		6,710	
1964	7,085		6,780	
1963	7,090		6,740	
1962	7,107		6,750	
1961	7,107		6,750	
1960	7,129		6,770	
1959	7,135		6,780	
1958	7,218		6,860	
1957	7,218		6,860	
1956	7,218		6,860	
1955	7,223		6,860	
1954	7,223		6,910	
1953	7,223		6,910	
1952	7,223		6,910	
1951	7,223		6,910	
1950	7,223		6,910	

a. 1973-1979 data from U.S. Department of Energy (1980a); 1972 and prior from U.S. Bureau of Mines, 1976.
b. Used by UN Statistical Office in preparation of 1980 Yearbook of World Energy Statistics (UN, 1982).
c. 1978-1980 data in parentheses are from Annual Bulletin of Coal Statistics for Europe (UN, 1981).

reduced heating values. Coal used at large U.S. electric power plants (>25 MW) had an average heating value of only 6078 cal/g (10857 Btu/lb) in 1976 and 6175 cal/g (11027 Btu/lb) in 1977 (National Coal Association, 1978). To have the reported amount of coal truly reflect the annual energy use (and carbon content), the United Nations has countered the decreasing heating values by applying correction factors to lower grade fuels and reporting coal equivalent tons.

Beginning with the publication of World Energy Supplies 1973-78, (identified by the UN as Series J, No. 22) in 1979, the UN staff has made efforts to insure that all coal is adjusted to coal equivalents. Between 1973 and 1979 there were adjustments for low grade hard coals in Norway, United Kingdom, Czechoslovakia, New Zealand, U.S.S.R., India, Pakistan, German Democratic Republic, and Hungary (UN, 1979). Prior to 1973 there was adjustment only for U.S.S.R. and Pakistan. Table 4 shows the progressive changes in world coal production reported by successive UN annual volumes. The World Energy Supplies series published prior to 1979 (J-19, J-20, J-21), indicate the changes made as a result of additional information or revisions of individual country data. Beginning with the World Energy Supplies (J-22), changes in the data are larger and consistently downward, reflecting the adjustments for reduced heating value of coals from more and more countries.

The changes between times of publication of J-22 and the 1979 Yearbook of World Energy Statistics (published in 1981) included not only downward adjustment made for lower grade coals, but also a beginning of a change from a higher heating value to a lower heating value basis ("gross heat value" to "net heat value," in UN terms). Thus, for example, the reduction in the value reported for 1975 between J-22 and the 1980 Yearbook is 246 million tons of coal equivalent (9.5 percent) and is the result of a combination of further adjustments for coal quality plus adjustment to "net heat value." The UN has now completed the shift to a "net heat value" basis for at least 60 percent of the world coal production. It appears that the coefficient to convert Chinese coal to coal equivalents also is on a "net heat value" basis and this would raise the percentage to 77 of the total world production. Table 3, column 2, gives the heating values used by the UN (1982) when converting tons of U.S. coal to tons of coal equivalent.

TABLE 4. WORLD COAL PRODUCTION AS REPORTED BY THE UNITED NATIONS STATISTICAL OFFICE IN SUCCESSIVE ANNUAL REPORTS
(in millions of tons of coal equivalent)

	UN World Energy Supplies (annual volumes)				UN Yearbook of World Energy Statistics	
	J-19	J-20	J-21	J-22		
Year	1950-74*	1971-75*	1972-76*	1973-78*	1979+	1980+
1979					2737	2614
1978				2784	2608	2476
1977			2775	2763	2570	2447
1976		2714	2702	2650	2482	2393
1975	2634	2640	2633	2577	2427	2331
1974	2513	2517	2503	2457	2325	2234
1973	2481	2483	2470	2426	2308	2220
1972	2439	2438	2426	2384	2275	2191
1971	2398	2397	2395	2362	2256	2173
1970	2420	2397	2399	2356	2260	2179

* Annual edition of World Energy Supplies, United Nations.

\+ Annual edition of Yearbook of World Energy Statistics (replaces World Energy Supplies), United Nations.

The UN decision to tabulate coal production on a "net heat value" basis complicates the computation of CO_2 emissions because most coal analytical data provide chemical composition and higher heating value. However, because the UN publications provide the most reliable and consistent set of global data for coal, we will continue to rely on them and make adjustment in the factor for the carbon content to accommodate the UN use of "net heat values."

In using the UN solid fuels values from the 1980 Yearbook of World Energy Statistics, one specific inconsistency was noted. Because the data published are based on coefficients converting to coal equivalents for all major coal producers except Poland, we have adjusted the world totals to reflect the application of such a coefficient (0.810) to Polish coal. This procedure was adopted after lengthy discussions with UN statistical office staff and we are assured that future UN data will likewise use a coefficient near 0.810 for Polish hard coal data. Thus the UN data for solid fuel production (as slightly modified) are the base used in calculating CO_2 emissions. These modified production data for solid fuels are in column 5 of the summary table (Table 14).

The estimation of uncertainty in the solid fuel data, already difficult, is made even more so because the process of revising the coefficients for coal equivalents is still in progress at the UN (but appears to be nearing completion). With some uncertainty still associated with the change to net heat value, we judge these data to include an uncertainty around 11 percent. This is based on an uncertainty of ± 5 percent for the production data in mass units and ± 10 percent on the conversion to a coal equivalence basis. Collecting these as $\sqrt{\Sigma E_i^2}$ where the E_is are the individual uncertainty estimates, we have $\sqrt{100 + 25} = 11.2$ percent.

Flaring of Natural Gas

The lack of markets and infrastructure for using natural gas as a fuel leads to massive flaring at oil fields in some remote locations. The UN makes no attempt to tabulate the amounts of natural gas flared from any

nation. Data for non-U.S. levels of natural gas flaring prior to 1971 are nonexistent. To develop a usable data set, Rotty (1974) used unpublished gas flaring data for 1968-1971 (included on questionnaires returned to the U.S. Bureau of Mines) with published oil production data from many countries to estimate a time series for gas flaring. Rotty assumed that essentially all gas flared is "associated gas" from oil fields where facilities for the recovery of the gas are not present and used the ratio of gas flaring to oil production for separate areas of the world. Although Rotty's numbers are somewhat speculative, they contribute a small fraction of the total emissions and are used here for the period 1950-70 without change.

Beginning about the time of Rotty's estimates, the U.S. Department of the Interior, and more recently the Department of Energy, have published annual values for the global flaring of natural gas. We use these data for the years 1971 through 1978 (DOI 1974; DOE, 1979; DOE, 1980b) but note that the published values are labeled "partly estimated." This data set appears fully compatible with the estimates of Rotty (1974) and this combination provides the best available consistent data sequence for global gas flaring (see Table 14).

Although there is no strong incentive to account for gas flaring, the recent data represent an attempt to account for this loss. Formal calculation of the uncertainty involved in these data would require more information than is available. The flaring of gas associated with oil production is at best as uncertain as the oil production, but the approximate agreement of the estimates of Rotty (1974) with attempts by DOE to tabulate a time sequence of recent global flaring suggests the uncertainty is not unbounded. We lack great confidence in all flaring data (earlier values in particular) and believe an uncertainty of ± 20 percent is appropriate here.

Production Data vs. Consumption Data

Carbon dioxide is emitted when fossil fuel is oxidized, i.e., consumed. Global fuel accounts are published as both fuel production and fuel consumption. The difference is not simply an increase or decrease in storage, but includes adjustments for various amounts of the fuel produced that are employed in many different end uses. In addition to use as common fuels and

in processing fuels, some is used as special fuel, some as "nonfuel" in which the carbon is quickly oxidized, and some as "nonfuel" in which the carbon remains unoxidized for very long times.

Keeling (1973) elected to use production data and make estimates of the fraction of the fuel that was ultimately oxidized. At that time fuel accounting for many parts of the world was not sufficiently advanced to provide suitable data sets to account for all the end uses all over the world. Production data have been and are more reliable and consistent from year to year. Using the fuel production numbers to calculate CO_2 emissions can be thought of as metering the man-induced carbon flow from the earth's crust to the atmosphere at the boundary where the carbon crosses the earth's surface.

Use of fuel consumption data might be intellectually more satisfying because it is in the consumption that the CO_2 is produced. However, the consumption data available cover what the UN calls "apparent consumption." The UN obtains apparent consumption by adding a country's excess of imports over exports to its production, and subtracting the amount used in bunkers and for increases in stocks. The amounts of consumption as tabulated by the UN have been consistently less than the aggregated amounts of production--even when changes in stocks are considered. Much of the difference appears to be in the use of fuel to produce fuel, particularly the use of oil in refineries to produce those products that make up the consumption numbers.

Coal and gas consumption data can easily give a reasonably accurate picture because very little transformation takes place between the raw (mined) fuel and the fuel used by the consumer. The calculation of emissions from inland consumption data for coal and gas is straightforward and gives results that are consistent and nearly identical with those determined from fuel production data. The fact that global imports of each fuel for a given year almost always exceed global exports indicates that "apparent consumption" data includes some accounting difficulty, but the difference is generally about 0.1 percent of production.

Crude petroleum presents a different problem in that almost none of the fuel is consumed as crude. Rotty (1982) attempted to reconcile the world production of crude petroleum and natural gas liquids with the consumption of liquid fuels and other petroleum products as tabulated by the UN Statistical Office. The balance he achieved for the liquid fuels account for 1979

is indicated in Table 5. In the same paper, Rotty (1982) calculated the 1979 CO_2 emissions from all of the fossil fuels on both production and consumption bases. When all of the fuel consumption data were considered along with properly corrected CO_2-factors, the calculations for 1979 showed a total of 5191 million tons of carbon as CO_2. For comparative purposes, the calculations based on production data showed a total of 5224 million tons--a difference of 0.6 percent. (Later in this report 5246 million tons of carbon is given as the result for 1979, the difference being a combination of using recently revised UN fuel data and new estimates for (FO) and (C) developed in the following sections.) Clearly, the difference between the result based on fuel consumption data and that based on fuel production data is small in comparison to the probable error in fuel statistics.

Because fuel production and consumption data are so closely linked and because the production data are easier to use and are more reliable as an historic data set, our computations will continue to rely on the fuel production data.

TABLE 5. 1979 WORLD LIQUID FUELS BALANCE SHEET

Production	Amount (10^3 Tons)	Consumption	Amount (10^3 Tons)	
Crude Petroleum Production	3,123,256	Loss of mass in Refineries (Used as fuel?)	112,934	(3.5%)
Gain in commerce of crude (Imports-Exports-Incr. Stocks)	22,567	Energy Products (2,816,763):		
Natural Gas Liquids to Refineries	38,004	Inland Consumption by Nations	2,604,505	(80.3%)
Subtotal, Input to Refineries	(3,183,827)	Bunkers (International)	152,039	(4.7%)
LPG from Natural Gas	60,071	Increase in Stocks	15,774	(0.5%)
		Loss in Commerce of Products (Exports-Imports)	44,445	(1.4%)
		Nonenergy Products (314,270):		
		Rapid Oxidation	118,343	(3.6%)
		Slow or Nonoxidation	195,927	(6.0%)
Total	3,243,898	Total	3,243,967	

From: Rotty (1982) based on data from 1979 Yearbook of World Energy Statistics, UN (1981).

FUEL FRACTION NOT OXIDIZED

As acknowledged in Equation 1, a fraction of the fossil fuel produced each year is not oxidized during time frames of interest here. Part of the unoxidized carbon results from incomplete combustion in burners (resulting in soot and unburned hydrocarbons) and part of it results from diversion of some of the produced "fuel" to nonfuel uses (e.g., use as raw materials for the chemical industries). In this section we derive values for FO_1 in Equation 1, the effective fraction of each year's production which is soon oxidized. In both the fuel and the nonfuel cases the hydrocarbons not burned are oxidized in the environment with times varying from very short (weeks or months) to many years. In the aggregate this slow (noncombustion) oxidation could be approximated by an exponential decay law. In such a situation, over long-time scales the amount oxidized each year will equal the amount produced each year as long as the amount produced each year is nearly constant. When the average lifetime of the unoxidized materials is very long or when the amount produced each year is growing, there is a net amount that remains unoxidized. Attempting to estimate production growth rates and decay rates for each unburned or incompletely oxidized hydrocarbon species would become extremely involved. Instead we have aggregated for all liquid fuels and have made subjective estimates of the extent to which production and net oxidation are likely to differ during a given year. Although this is never fully satisfying it is important to recognize that most of the hydrocarbons are oxidized as fuels and that the data cited do provide close bounds for the fractions which are likely not to be oxidized. The probable error introduced through this aggregation and estimation procedure is small in comparison to uncertainties in the fuel production data and more rigorous examination of the noncombustion oxidation rates does not seem justified for the calculation of CO_2 emissions.

Natural Gas Produced but Not Oxidized

As illustrated in Figure 1, most of the natural gas produced in the U.S. is used for fuel. Data required to obtain the nonfuel use of natural gas globally are not available in formal references so we have based our

estimates on what data are available for the U.S. Nonfuel gas use in the U.S. is no longer being published by the Department of Energy but we note the mean value for 1970-76 is 3.16 percent of production (Table 6). The lack of markets and infrastructure for using natural gas as a fuel leads to massive flaring at oil fields in some parts of the world and also leads us to expect that the fraction of marketed gas that ends up in nonfuel uses may be significantly larger in those areas than in the U.S. On the other hand, the total world production is still dominated by countries like the U.S., the U.K., Canada, and the Netherlands where gas is largely used as a fuel. Based on the data for the U.S. given in Table 6, we estimate that global nonfuel use of gas is about 3 percent of production. Because the nonfuel use is small, any error in basing the estimate on the biggest producers gives uncertainties that are small fractions of total marketed production. A large fraction of the nonfuel gas goes to ammonia production during which the carbon in the gas is mostly oxidized; the remainder to uses in which the carbon will be oxidized at varying rates over a period of years. The total quantity for nonfuel use has been increasing with time and, in accord with the principle that slowly oxidizing material decays exponentially with time, this suggests that a small amount of unoxidized gas accumulates each year. As a result of increasing nonfuel use and the production of long-lifetime products, we assume that, over time, an amount of carbon equivalent to two-thirds of the carbon in each year's nonfuel-use gas is oxidized during that year. Because nonfuel use is 3 percent of production, this is the same as assuming that, on the average, 1 percent of each year's produced gas remains unoxidized for long periods as a result of nonfuel uses.

Because of incomplete combustion, a small amount of the carbon in the gas used as a fuel will not be oxidized and will remain as soot either around the burner, in the stack, or in the environment. Although the amount of unoxidized carbon is impossible to determine on a global scale, it is extremely small in modern combustion systems and we use, as an upper limit, that 1 percent of the carbon in gas produced globally remains unoxidized during combustion processes.

For natural gas the fraction of annual production remaining unoxidized each year is thus taken to be 0.02, i.e. 0.01 for unoxidized nonfuel uses and 0.01 for unoxidized carbon in combustion. The sequence of assumptions

TABLE 6. NONFUEL USE OF U.S. NATURAL GAS
(10^6 cubic meters)

Year	Gas Production	Nonfuel Use	Nonfuel as % of Production
1976	540,599	17,415	3.22
1975	545,124	16,819	3.09
1974	580,788	20,109	3.46
1973	615,784	19,813	3.22
1972	618,768	18,518	2.99
1971	618,582	18,369	2.97
1970	601,309	18,856	3.14
1970-76 average			3.16

Gas production data from 1979 Yearbook of World Energy Statistics, UN (1981). (Heating value of U.S. natural gas of 38,017 Kjoules/m^3.) Nonfuel use is from API (1977).

here imposes an uncertainty on the gas oxidized of about one percent of the gas produced. Thus the fraction of gas oxidized is $FO_g = 0.98 \pm 0.01$.

Liquids Produced but Not Oxidized

A key question for CO_2 production from crude oil and natural gas liquids is the fraction of production which is burned or otherwise oxidized on a short time scale as opposed to that which ends up in e.g., fibers, lubricants, or paving materials, and is oxidized only over a longer interval.

The United Nations statistics separate refinery output into energy products (aviation gasoline, motor gasoline, jet fuel, kerosene, gas-diesel oil, residual fuel oil, LPG, and refinery gas) and nonenergy products (naphthas, white spirits, lubricants, bitumen (asphalt), petroleum waxes, petroleum coke, and others) with the nonenergy products comprising 10.2 percent of the total in 1979. United Nations data also distinguish the components of natural gas liquids (natural gasoline, condensate, LPG, and "other natural gas liquids"). With the exception of some of the LPG, most of the natural gas liquids are consumed as fuels.

Turning again to United States data for guidance, we find in Figure 2 that about 12 percent of U.S. refinery output in 1981 is "other" products. Table 7 subdivides this "other" category and allows identification of petroleum fractions which are used in ways that do not lead to immediate oxidation. In addition, a major fraction of the liquified petroleum gases and ethane in Figure 2 may not undergo prompt oxidation. The total remaining unoxidized depends to a large degree on both the amounts used in the petrochemical industry and the way in which those products are used. Without a belabored analysis of the world petrochemical industry, we use U.S. data as an analog in making estimates of unoxidized carbon from UN data. Starting with the UN tabulations for refinery nonenergy products and the LPG and ethane from gas liquids plants, we estimate the fraction that is likely to remain unoxidized for long periods of time.

Most of the LPG from refineries is probably consumed as fuel and the UN lists LPG as an energy product from refineries. Therefore, we estimate the amount of LPG and ethane that is used in the petrochemical industry as a

TABLE 7. 1981 U.S. REFINERY OUTPUT OF "OTHER" PRODUCTS
(See Figure 2)
(10^3 bbl)

Natural Gasoline	42,363
Unfractionated Stream	182
Aviation Gasoline	11,147
Petrochemical Feedstocks	208,861
Special Naphthas	27,018
Lubricants	55,958
Wax	6,581
Coke	91,868
Asphalt	123,982
Road Oil	760
Still Gas for Fuel	206,339
Miscellaneous Products	36,213
DOE Reclassification (Adjustment)	-98,214
	713,118

From: U.S. Department of Energy (1982b), DOE/EIA-0340(81)/1.

fraction of only the LPG and ethane produced in natural gas liquids plants. This does not imply that all the LPG used in the petrochemical industry comes from gas processing plants, but only that the global quantity can be best estimated as a fraction of the LPG produced in gas processing plants. In the U.S., the 232.76 million barrels of LPG and ethane sold for chemical and industrial uses in 1981 represents 50.7 percent of that produced in gas processing plants. The industrial sales include use as a standby fuel, in space heating, flame cutting, metallurgical furnaces, and plumber's torches. They also include sales for use as refinery fuel. Chemical use includes those gases employed as raw materials, solvents, and in the production of synthetic rubber. Data for 1981 are not available, but in 1979 the split was 80 percent to chemical use and 20 percent to industrial fuel use. Thus, the equivalent of (0.8)(50.7) = 40.6 percent of the LPG and ethane produced in U.S. natural gas liquids plants is used in applications in which oxidation occurs very slowly. Because the petrochemical industry outside the U.S. depends more heavily on feedstocks from refineries, especially certain napthas, we estimate that, on a worldwide basis, about 40 percent of the LPG and ethane produced from natural gas processing plants ends up in materials which are not soon oxidized.

In the United Nations tabulation of nonenergy refinery products, what is defined as napthas is largely used as chemical feedstocks, and nearly half of the petrochemical feedstocks in Table 7 is naptha. This is a major feedstock to the western Europe petrochemical industry and we estimate that about 80 percent of the napthas produced globally remain unoxidized for long times in plastics, tires, and fabrics.

A substantial part of the nonenergy refinery products is asphalt. Even when paved roads, parking areas, and roofs deteriorate or are removed, most of the asphalt remains in an unoxidized state. Thus, assuming that virtually all of the UN reported asphalt production from petroleum refineries remains unoxidized for long periods introduces a small overestimation. Petroleum waxes are used in manufacture of candles, polishes and waterproofing of containers, wrappings, etc. White spirits are used as paint solvents and as dry cleaning materials. Petroleum coke is mostly used in metallurgical processes and the fraction of the carbon that remains unoxidized is probably small. We estimate these nonenergy products except

asphalt are mostly oxidized rather promptly and that assuming full oxidation introduces small error of opposite sign from assuming that all asphalt is not oxidized.

The UN category of lubricants gives us a problem because a non-negligible part of lubricating oil is oxidized in use. Spillage and oil drained from engines are frequently flushed into other waste liquid streams or disposed of in absorbants or containers in land fills. We have used the estimate that approximately 50 percent of lubricants produced by petroleum refineries remain unoxidized for long periods of time.

Our assumption is that, allowing for errors of both inclusion and omission, the quantity of liquid fuels not oxidized each year is approximated by the sum of 40 percent of the LPG and ethane from gas liquid plants, 80 percent of the napthas from petroleum refineries, all of the asphalt, and 50 percent of the lubricants. This is summarized in Table 8. The conclusion is that 6.5 to 6.9 percent of petroleum liquids is not soon oxidized and we adopt 6.7 percent for our computations. For comparison Hatch and Matar (1977a) reported that in 1974 6.5 percent of world crude went into petrochemicals. Also, Flavin (1980) estimated that 1979 production of synthetic materials amounted to 10 million tons of synthetic rubber, 10 million tons of synthetic fiber, and 60 million tons of plastic. The sum of the unoxidized LPG, ethane and napthas in Table 8 is 93.5 million tons. Our analysis suggests it is unlikely the true value of unoxidized liquids is greater than 8.7 percent or less than 4.7 percent of annual production.

Having based this analysis on data for the last decade, there remains the question of changes in the unoxidized fraction during earlier decades in the 1950-1981 period. United Nations data on nonenergy products from refineries for 1970-1980 published in the 1979 and 1980 Yearbooks of World Energy Statistics differ markedly from those published in 1976, the most recent figures being, on average, a factor of 1.33 larger for the 5 years of overlap. Thus, we assume that data for nonenergy products before 1970 are subject to sizable revision and a better estimate of nonoxidative uses can be obtained by applying a 1971-1980 average to the crude production uniformly rather than trying to itemize nonenergy uses. API (1975) data also suggest that the time dependent bias implicit in carrying a constant fraction back to 1950 is small. Lacking better information, we shall use the 6.7 percent factor for the entire 1950-1981 period.

TABLE 8. ESTIMATE OF WORLD PETROLEUM LIQUIDS PRODUCED BUT NOT OXIDIZED EACH YEAR (10^3 tons)

	40% of LPG & Ethane from Gas Plants	80% of Naptha	Asphalt	50% of Lubricants	Total	% of Liqu Prod
1980	25,754	58,541	97,941	19,649	201,885	6
1979	25,989	67,500	101,508	19,700	214,697	6
1978	23,382	66,025	97,760	18,448	205,615	6
1977	23,169	66,412	91,372	17,560	198,513	6
1976	22,196	65,853	85,904	16,543	190,496	6
1975	21,864	56,194	85,722	15,578	179,358	6
1974	21,809	70,862	88,141	17,196	198,008	6
1973	21,232	70,581	90,048	16,489	198,350	6
1972	20,178	60,749	83,568	15,201	179,696	6
1971	18,477	55,382	80,415	14,819	169,093	6
						av. 6

1976-1980 data from 1980 Yearbook of World Energy Statistics, UN (1982).
1971-1975 data from 1979 Yearbook of World Energy Statistics, UN (1981).

The other situation for which we should make some adjustment in the CO_2 computation is the failure to achieve 100 percent combustion of fuels actually delivered to burners. Carbonaceous materials that are discharged not completely oxidized include those, like CO, which undergo complete oxidation fairly promptly in the environment; others, like soot, which do not oxidize in times of interest; and others, like methane, which oxidize in the environment at a rate such that some finite fraction is oxidized in the first and each succeeding year of interest. For this third class of compounds any difference between the total amount of carbon being oxidized in a given year and an estimate thereof based on full oxidization of current year discharge must be a consequence of an increase in production rate. The simple assumption of an equivalent fraction of material not oxidized during a current year will not introduce significant error so long as the total fraction of material in this class is small.

To estimate the fraction of liquid fuel which goes to burners but is not fully oxidized, we used Environmental Protection Agency estimates of nationwide pollutant emissions in the U.S. In 1976, U.S. emissions of hydrocarbons to the atmosphere amounted to 27.9×10^6 tons, of which 14.7×10^6 tons were related to transportation and oil and gas refining, production, and marketing (Table 9). Another 1.4×10^6 tons were from stationary fuel combustion sources. Of the 13.4×10^6 tons of total suspended particulates discharged to the atmosphere, 1.3×10^6 were from transportation and petroleum refining with another 4.6×10^6 from stationary fuel combustion sources. Table 9 lists emissions from many sources, but we are concerned here only with those associated with combustion of liquid fossil fuels, having already discounted quantities for nonfuel uses such as organic solvents.

In these calculations we assume that half of the hydrocarbons and one-fourth of suspended solids from stationary fuel combustion represent carbonaceous materials attributable to burning liquid fuels, the remainder from other fuels. Then, for the United States, 15.4×10^6 tons of hydrocarbons and 2.5×10^6 tons of suspended carbonaceous particulate material represent incompletely oxidized liquid fuels from combustion applications. If this material undergoes oxidation in the environment over time (some of it very slowly), we can consider that some fraction of 17.9×10^6 tons represents the portion of the 1976 U.S. liquid fuel consumption which should not be counted as CO_2 production.

TABLE 9. 1976 U.S. EMISSION OF HYDROCARBONS AND TOTAL SUSPENDED PARTICULATES*
(10^6 tons/year)

Source Category	TSP	HC
Transportation	1.2	10.8
Highway Vehicles	0.8	9.3
Nonhighway Vehicles	0.4	1.5
Stationary Fuel Combustion	4.6	1.4
Electric Utilities	3.2	0.1
Industrial	1.1	1.2
Residential, Commercial and Institutional	0.3	0.1
Industrial Processes	6.3	9.4
Chemicals	0.3	1.6
Petroleum Refining	0.1	0.9
Metals	1.3	0.2
Mineral Products	3.2	0
Oil and Gas Production Marketing	0	3.0
Industrial Organic Solvent Use	0	2.9
Other Processes	1.4	0.8
Solid Waste	0.4	0.8
Miscellaneous	0.9	5.5
Forest Wildfires and Managed Burning	0.6	0.8
Agricultural Burning	0.1	0.1
Coal Refuse Burning	0.1	0.1
Structural Fires	0.1	0
Miscellaneous Organic Solvent Use	0	4.5

* From: U.S. Environmental Protection Agency (1977).

Many of the hydrocarbons emitted, especially from engine exhausts, are partially oxidized and hence highly reactive (NRC, 1979). Data on selected urban aerosols suggest that the aerosols are on the order of 20 percent carbon and that 30-40 percent of this carbon is graphitic soot and the remainder primary and secondary organic material (NRC, 1979). The total, 17.9 x 10^6 tons, represents about 2.4 percent of the 751 x 10^6 tons of liquid fuels consumed in the U.S. in 1976. Because a fraction of the 17.9 x 10^6 tons is oxidized in the environment in a realtively short time, something approximating 1.5 ± 1 percent of the liquid fuel that goes to burners each year remains in the environment unoxidized.

The U.S. data can only provide a useful approximation of the extent of unburned material globally. The amount unburned is clearly a small fraction of the total and we note that U.S. emissions of some materials have declined in recent years because of technological improvements. Our procedure probably gives low estimates of global emissions of unburned carbon (and hence high CO_2 estimates). In addition, the assumption of a constant 1.5 percent for the unburned fuel introduces some time-dependent bias in the estimate.

The total mass of liquid fuels lost directly to the environment is not large in comparison to the amount produced. Oil spills at sea amounted to 237,600 tons in 1978 (UN Environment Programme, 1979) and there are smaller but much more numerous losses thoughout the processing/delivery system. Loss of organic compounds as liquid effluent at an oil-fired power plant is estimated to be on the order of 15 percent of the airborne hydrocarbons (UN Environment Programme, 1979). None of these is large enough to make a significant correction to the calculations already detailed.

In summary, about 6.7 ± 2 percent of the liquids produced end up in petrochemical applications where they are not soon oxidized and another equivalent fraction of 1.5 ±1 percent passes through burners and is deposited in the environment without being oxidized. We believe the factor for oxidation of liquid fuel produced is $FO_1 = (1 - 0.082) = 0.918 \pm 0.03$.

Solid Fuels Produced but Not Oxidized

Incomplete combustion results in the discharge from boilers of coal dust, gaseous hydrocarbons, and unburned char. The concentration of carbon

monoxide (CO) in flue gas can be used as a first order indicator of the completeness of the combustion process and data on CO emissions collected by the U.S. National Air Pollution Control Administration (1970) show that emission factors depend strongly on the type and size of the coal-burning unit. Carbon monoxide emissions per unit of energy can be two orders of magnitude larger from small and/or less efficient units than from large, modern pulverized-coal boilers. Any attempt at a general, time-independent factor to compensate for incomplete combustion must recognize that, for example, 82 percent of the U.S. coal consumed in 1981 was burned in utility boilers while only 17 percent was so burned in 1949 (Figure 3). Transportation accounted for 15 percent of U.S. consumption in 1949 and virtually none in 1981. Employing a constant for the unburned fuel fraction for both current U.S. electric utility boilers and steam locomotives is, of course, only marginally justifiable, and then only because the total fuel used in locomotives (in 1949, for example) was on the order of one-tenth of present solid fuel use.

The United Nations Environment Programme (1979) has estimated that of 3×10^6 tons of coal burned in a 1000 MW(e) power plant, 860 tons of carbon end up in CO, 3000 tons as particulates, and about 400 tons in unburned hydrocarbons. If we assume, as a first approximation, that the CO and unburned hydrocarbons are soon fully oxidized in the environment (Chameides and Davis [1982] show the lifetimes of CO and methane in the atmosphere as about 65 days and 7 years, respectively) while the particulate matter remains largely unoxidized, the unoxidized fraction will amount to only 0.14 percent of the carbon. By contrast, Harding (1920) has written "probably the worst fuel loss that a locomotive fireman has to contend with is that which occurs through the escape of unburned fine coal. When the percentage of fine coal is very high, this loss may amount to one-quarter or even one-third of the coal fired," and "even at best there is considerable fuel loss through soot."

Block and Dams (1976) compared the composition of fly ash from an industrial boiler (24-hour capacity of 14 tons of coal) with that of a small home furnace in Belgium (24-hour capacity of 24 kg of coal). The concentrations of inorganic components in fly ash from the home furnace were 2-10 times smaller than in the industrial boiler, apparently due to dilution with

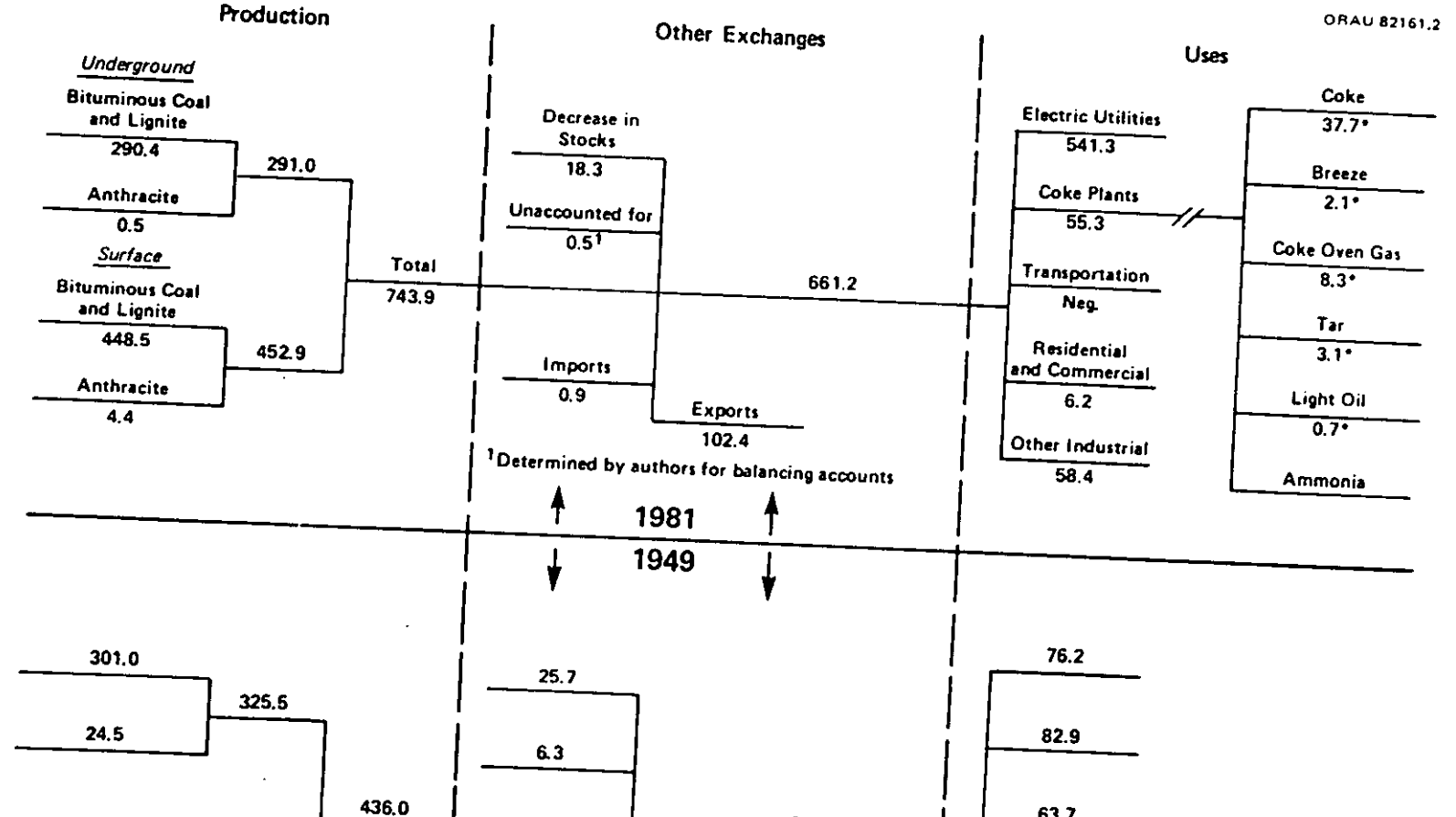

Figure 3. U.S. Flows of Coal in 1981 and 1949 (in millions of metric tons)
Data from *Coal Data: A Reference*, DOE/EIA-0064(82), (1982c); and *Coke and Coal Chemicals in 1980*, DOE/EIA 120(80), (1982d).

*The most recent data available for coke plant products are for 1980 when 60.5 million metric tons of coal were consumed by coke plants. Data are in coal equivalents with both data and heating values taken from *Coke and Coal Chemicals in 1980*. Coke converted to coal equivalents at 0.9 from UN, 1981.

large emissions of unburned material. Unburned material comprised about 35 percent of the fly ash from the home furnace.

Another useful perspective can be obtained by examining data from current large coal consumers. Data on combustion efficiency at the Tennessee Valley Authority's Bull Run Steam Plant show that 1 percent of the stack ash is combustible matter; for the Shawnee Plant 5 percent is more typical, and during a recent period of poor performance the Widows Creek Plant ran between 9 and 20 percent combustible matter in the fly ash. Because these plants operate on pulverized coal with about 80 percent of the ash being collected by the stack precipitators, this is probably representative of the average fraction of unburned coal. Taking a representative value of mean ash content for the coal of about 12 percent, between 0.14 and 2.7 percent of the combustible fraction of the coal remains unburned. Typical values are near 0.7 percent and the lower limit is similar to the UNEP number cited above. The Belgian home mentioned above was burning anthracite with 3.1 percent ash, implying that 1.1 percent of the coal was discharged unburned.

With this information it seems reasonable to assume that about 1 ± 1 percent of the carbon in coal currently supplied to furnaces is discharged unoxidized. Using this fraction over the full 1950-present interval probably introduces a time-dependent bias because the number has almost certainly been decreasing with time.

The other adjustment for unburned coal has to do with coal which is used for nonfuel purposes. Figure 3 shows the flow of U.S. coal from the mine to the sectors in which it is ultimately consumed and allows identification of the principal portion which is not used as a fuel. Of coal which is used for coking, two by-products form the bases for a very large chemical industry--the crude light oil and crude tar of Figure 3. The quantities of light oil and tar shown in the figure are given in coal equivalents by heating value. Of the coal tar fraction, some 21 percent is typically used for fuel while benzene (21 percent), creosote oil (20 percent), and road tars (17 percent) are the other principal products (Wainwright, 1977). Benzene, toluene, and xylene typically account for 75 percent of the crude light oil.

Thus it appears that about 75 percent of the coal equivalents which are accounted for as light oil and tar represent the coal which ends up in applications where oxidation is long delayed. From U.S. data, Table 10

TABLE 10. LIGHT OIL AND TAR PRODUCED FROM COAL IN U.S. COKE PLANTS
(in millions of tons coal equivalent by heating value)

Year	Crude Light Oil and Crude Tar	Coal to Coke Plants	% Coal Converted to Light Oil and Tar
1980	3.630	60.510	6.00
1979	4.014	69.944	5.74
1978	3.677	64.773	5.68
1977	4.034	70.488	5.72
1976	4.363	76.838	5.68
1975	4.398	75.840	5.80
1974	4.676	81.828	5.71
1973	5.013	85.366	5.87
1972	5.037	79.560	6.33
1971	4.612	75.477	6.11
1970	5.251	87.543	6.00
1969	5.363	84.731	6.33
		12-year Mean	5.91

From: U.S. Department of Energy (1982c, 1982d) and U.S. Bureau of Mines (1973).

shows that on average 5.91 percent of the coal going to coke plants ends up as light oil and crude tar, and 75 percent of that, or 4.4 percent has oxidation long delayed. Using this number and statistics for world coke, we can estimate the fraction of the global coal production that does not enter the CO_2 route. This calculation of the mass of U.S. nonfuel coal use agrees within 5 percent with the numbers compiled by Dupree and West (1972).

There are three other considerations associated with coal production that could affect CO_2 releases. These are burning of wasted coal on abandoned mine lands, methane ventilated from coal mines, and the use of SO_2 scrubbers at coal-burning plants.

Chaiken (1980) cites a 1968 U.S. Bureau of Mines survey that found 292 waste banks on fire and in a 1977 survey 261 coal deposits in the U.S. were classified as burning. The 292 waste banks contained an estimated 49 million tons of coal. Even if all of this coal was burned over a ten-year period it would still amount to less than 1 percent of U.S. coal consumption. Although it is difficult to estimate tonnages involved, burning in coal deposits is probably no greater than burning on waste piles. The U.S. Environmental Protection Agency (1977) has estimated that coal refuse burning contributes 0.3 percent of U.S. carbon monoxide emissions, but because refuse burning occurs in an oxygen-deficient environment, the contribution to carbon monoxide discharge should be a much larger fraction than the contribution to carbon dioxide discharge. Thus much less than 0.3 percent of the CO_2 emissions can be attributed to this source, and ignoring this as a source of CO_2 seems to be justified.

In considering methane ventilated from coal mines, the content of gas in coalbeds varies considerably but Science Applications, Inc. (1980) estimates an average of 6.25 cubic meters per ton in bituminous coal and anthracite, 2.5 cubic meters per ton in subbituminous coal, and 1.25 cubic meters per ton in lignite. Coal mined in the U.S. in 1979 was composed of 622 million tons of bituminous coal, 109 million tons of subbituminous, 43 million tons of lignite, and 4 million tons of anthracite (U.S. DOE, 1981). The ratio among the four types is .799/.140/.055/.006 (although this has been changing in recent years with increasing amounts of lower grade coal being used) and using methane emission rates of 6.25/2.50/1.25/6.25 cubic

meters per ton respectively, the total methane emissions from U.S. coal mined in 1979 were (at an average of 5.45 m^3/ton) 4.24 x $10^9 m^3$. Fully oxidized, this would produce 2.16 x 10^{12}g C as CO_2. Again this number is a very small fraction of a percent of the emissions from coal burning and will be ignored.

The use of SO_2 scrubbing at coal burning plants is still at a sufficiently small scale that it too can be safely ignored as a source of CO_2 to the atmosphere. Coal with 1.5 percent S and 7,000 cal/gm (12,6000 Btu/lb) would discharge 2.381 lb SO_2 per million Btu (1.025 Kg/Kjoule). If SO_2 emissions were limited to the current 0.6 lb SO_2 per million Btu, scrubbing would have to collect 1.781 lb SO_2 per million Btu or 0.0112 tons S per ton of coal. Approximating the SO_2 scrubbing reaction as a stoichiometric exchange of C for S in the gas phase means that the collection of 0.0112 tons S would release 12/32 (0.0112) = 0.0042 tons of carbon per ton of coal. Widespread use of SO_2 scrubbing in the future could result in a small but measurable increase in the CO_2 emission rate.

The conclusion at this point is that from the total mass of coal mined (in tons coal equivalent on a 7,000 cal/g basis) we will subtract 4.4 percent of the mass which goes to coke plants (about 0.8 percent of the coal mined) to accommodate long-term nonoxidative uses, and subtract 1 percent of the remainder to accommodate the fraction which passes through furnaces without being oxidized. Our factor for oxidized fraction of world solid fuel production is thus $FO_s = (1 - 0.008)(1 - 0.01) = 0.982 \pm 0.02$.

CARBON CONTENT OF FUELS

The remaining component required to calculate CO_2 emissions is the global average carbon content of each fuel group (C_i in Equation 1). Because carbon content is correlated with heating value, and because the UN tabulation of gases is in terajoules and of solids in tons of coal equivalent at 7000 calories per gram, the resulting calculations are straightforward.

Gases

Although there are compositional data available for many individual natural gases, we have been unable to locate any statistical summary of the composition of natural gases produced over large geographic areas. From the analytical data for 252 wellhead samples of wet gas from 17 states as analyzed by the U.S. Bureau of Mines in 1976 (Moore, 1977), we eliminated those few samples least likely to be produced as fuels or indicating contamination (i.e., those with heating values less than 8010 kcal/m^3 [900 Btu/SCF] or oxygen concentrations greater than 0.2 percent). For the remaining data, a mean composition was calculated for samples from each state having data available; then these state means were weighted according to the marketed production for that state and a "weighted mean" for the United States as a whole was calculated (Table 11, column 1). This we call the 1976 U.S. reference gas. For comparison a similar "weighted mean" from the 373 samples analyzed in 1970 (Cardwell and Benton, 1971) was calculated and, using their 1970 data, simple unweighted national means and standard deviations were tabulated (Table 11, columns 2, 3, and 4).

Similarly, 174 non-U.S. samples from 18 countries were used to calculate individual country means; data from these 18 countries were combined with the U.S. data by weighting each according to 1970 production statistics to produce a world mean composition (Table 11, column 5)(data from Moore, 1976). This aggregation includes countries which represent 75 percent of the world production but does not include the USSR.

The 1976 U.S. reference gas composition (Table 11, column 1) should closely describe natural gas reported by the U.S. Bureau of Mines and U.S.

TABLE 11. COMPOSITION OF NATURAL GAS
(in volume percent)

	1976 U.S. Reference Gas	1970 Weighted U.S. Mean	1970 Unweighted U.S. Mean	1970 Unweighted U.S. Standard Deviation	(circa 1970) Weighted World Mean	1976 Adjusted Dry Gas
Methane	88.32	89.32	86.63	9.63	89.24	92.88
Ethane	4.65	4.66	5.02	3.52	4.52	3.91
Propane	2.12	2.04	2.57	2.56	1.95	0.62
Other Hydrocarbons	1.53	1.56	1.88	---	1.54	---
CO_2	0.92	0.65	0.63	1.11	0.78	---
Other	2.46	2.33	3.26	---	2.42	2.59
Higher Heating Value						
$kcal/m^3$	9685.60	9723.69	9859.31	1010.85	9680.26	9102.62
(Btu/SCF)	(1088.39)	(1092.66)	(1107.90)	(113.59)	(1087.78)	(1022.87)

Department of Energy, as "marketed production." Marketed production means wet gas and the "extraction loss" shown in the gas flow accounts represents processing to remove liquids which subsequently appear in the accounts as "natural gas liquids." The change in gas composition which occurs during the removal of natural gas liquids results in a reduction of heating value. For dry natural gas delivered to customers in 1976, the American Gas Association (1979) reports 9086 Kcal/m^3. Taking the 1976 reference gas, assuming removal of 20 percent of the ethane, 72 percent of the propane (Hatch and Matar, 1977b), all of the heavier hydrocarbons, and all of the H_2S, CO_2, and H_2O, the resulting gas (Table 11, column 6), has a calculated heating value of 9103 Kcal/m^3. This adjusted "dry gas" should closely resemble the composition of gas delivered to U.S. customers in 1976 and that counted by the UN as gas production. For other years the composition should be closely approximated by using the same wet gas composition and adjusting to the heating value of delivered gas, as published by the American Gas Association (see Table 12). This is done by removing appropriate amounts of "natural gas liquids," ethane and heavier hydrocarbons and recognizing that this removal has become increasingly efficient with time.

The 1976 adjusted dry gas contains 0.550 grams of carbon per liter at 0°C and, with the separated CO_2 included, would discharge 0.555 grams of carbon per liter as CO_2 when completely oxidized. Adjusted to 60°F (15.6°C) the temperature at which U.S. gas volumes are measured, and assuming ideal gas behavior, this amounts to 525.4 gC/m^3 or 57.75 gC/1000 Kcal. Doing similar calculations for the other mean gas compositions, we found that the carbon content per unit of energy could be closely represented by a linear relationship with heating value.

This relationship is expressed by the equation,

$$C_g = 57.357 + 1.459 \times 10^{-3} (\Delta H_H - 8898) \qquad \text{Eq. 2}$$

where C_g is the amount of carbon, (in gC/1000 Kcal), and ΔH_H is the higher heating value of the gas (in Kcal/m^3 at 15.6 °C). Equation 2 shows that the carbon content per unit of energy of the gas is not very sensitive to the heating value of the gas. Even though the heating value of "average" natural gas has changed slightly with time (as shown in Table 12), little information is lost by assuming a time averaged heating value. The 1970-80 world average is 8884 Kcal/m^3 (37,172 Kjoules/m^3). For the following reasons we have adopted the upward rounded value of 8,900 Kcal/m^3:

TABLE 12. MEAN HEATING VALUE OF DRY NATURAL GAS

	U.S.[(a)] ($Kcal/m^3$)	World[(b)] ($Kcal/m^3$)
1980		8825
1979	9068	8839
1978	9068	8851
1977	9086	8852
1976	9086	8864
1975	9112	8874
1974	9086	8893
1973	9139	8921
1972	9175	8924
1971	9175	8929
1970	9175	8956
1969	9175	
1965-1968	9184	
1964 and before	9211	

NOTES:

(a) From American Gas Association (1979), except 1979 value from U.S. DOE (1980a).

(b) These values are derived by using a representative (constant) heating value of gas from individual countries as reported in the 1980 Yearbook of World Energy Statistics, UN (1982), and calculating a weighted mean, based on annual production statistics. The weighted means are based on the 6 countries that have dominated world gas production over the last decade: U.S., USSR, Netherlands, Canada, UK, and Romania. The decline in the heating value so determined is a consequence of changing fractions of world total being supplied by the U.S.S.R. and Netherlands.

1. Heating values for individual countries are not well known, but the UN reports larger values for most small producers not included in our average,
2. The pre-1970 values were probably higher because U.S. gas made up a larger fraction of the total,
3. The carbon calculation is not very sensitive to small changes in heating value.

The regression equation then gives

C_g = 57.36 gC/1000 Kcal.

This is equivalent to Cg = 13.70 tons C/terajoule, and implies that "average" natural gas contains 510 gC per cubic meter. The value for carbon content of gases obtained by this procedure appears to be accurate to within ± 2 percent.

For flared gas there are no data from which to estimate the carbon content directly. Because flared gas is largely associated gas from oil fields it seems unlikely that its heating value is as low as is suggested by the heating value we have used for our global mean gas (heavily affected by Soviet gas). Although some gas is flared without processing, in other cases gas liquids are recovered before flaring. In view of these considerations, the assumption that gas flared globally has a carbon content close to that of dry gas marketed in the U.S. (525 gC/m^3) appears reasonable. Because flared gas almost certainly contains more carbon than the "average" global gas (510 gC/m^3), and gas with more than 540 gC/m^3 would be most unusual, the uncertainty on the assumed value of 525 gC/m^3 (0.525×10^3 gC/m^3) is taken to be ± 3 percent.

Liquids

Crude oil is a complex collection of hydrocarbons with about 600 individual hydrocarbons identified to date. The American Petroleum Institute's detailed analysis of Ponca City Crude isolated some 295 hydrocarbons which made up 60 percent of the total crude. "The remaining 40 percent undoubtedly consists of thousands of compounds many of which will never be identified" (Hunt, 1979, p. 34). Petroleum is the raw material for an estimated 7,000 end-use chemicals. Thus the analysis of crude petroleum for CO_2 emissions could be extremely complex.

Variations in petroleum are most often expressed in terms of its specific gravity at 60°F (15°C). The API gravity, where

$$\text{API gravity} = \frac{141.5}{\text{specific gravity}} - 131.5, \qquad \text{Eq. 3}$$

is an indication of the molecular size, carbon/hydrogen ratio, and hence carbon content of a crude oil. Coleman et al. (1978) have assembled analytical data, including API gravity, for 800 important U.S. crudes representing major fields and producing formations. The gravities of this sample varied from 8.9 °API (specific gravity = 1.0078) to 62.9 °API (specific gravity = 0.7279) with a mean of 34.75° API (specific gravity 0.8511) and a standard deviation of 7.71 °API. There is a similar diversity among major world sources of crude and even for the U.S. the mean of 34.75 °API is only indicative because it treats all 800 analyses equally without regard for production rate. According to Carter (1979), the average gravity of world crude varied between 32.0 and 32.9 °API for the years 1970-1979 and might be expected to drop only slightly lower over the next 5 years. Carter shows North American averages between 31.8 and 32.2 for those years.

For converting volume to mass units the U.N. (1982) assumes U.S. crude oil has a specific gravity of 0.848 (35.4 °API). We used U.N. single-country values for specific gravity and took the weighted average value for the 10 largest crude producing countries in 1978 (77 percent of the total). The result was a specific gravity of world crude of 0.857 (33.6 °API). Considering this in combination with Carter's conclusion, world average crude appears to have an API gravity of 32.5° ● 2°.

In Figure 4 we have plotted percent carbon versus API gravity for a few typical North American crudes (Marks, 1978). There is a good correspondence between percent carbon and gravity with 32.5 °API suggesting a composicion of about 85.25 percent carbon. Brame and King (1967) give a range of 79.5-87.1 percent carbon for crudes, with a mean of 84.5 percent carbon and Hunt (1979) also lists 84.5 percent as the carbon content of crude oil. The mean carbon content of crude oil will vary slightly from year to year as the

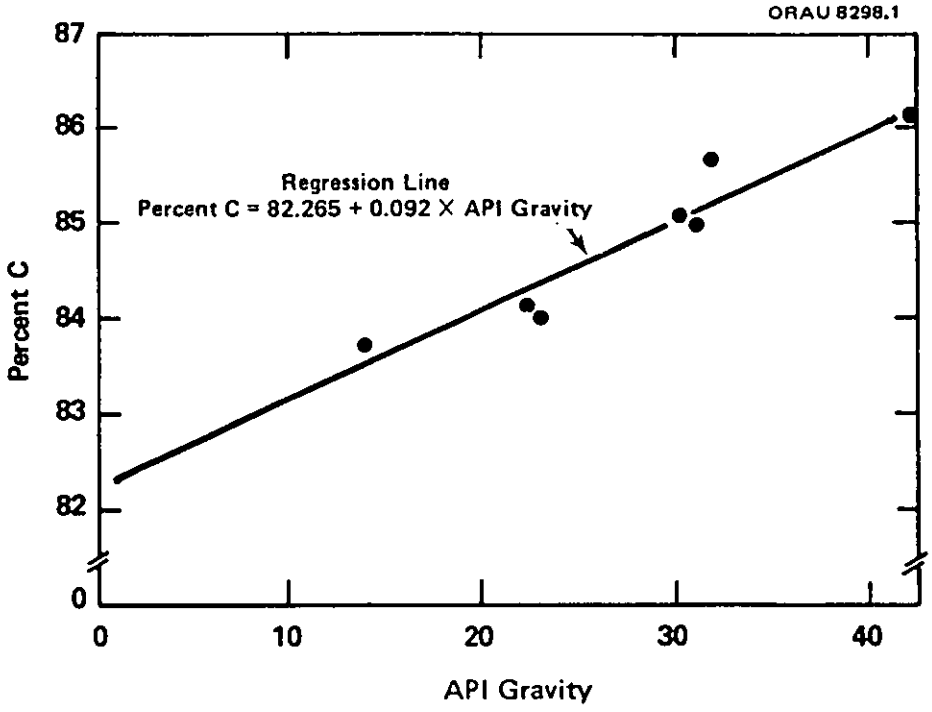

Figure 4. Percent Carbon as a Function of Specific Gravity for Samples Typical of North American Crude Petroleum

distribution of sources changes, and we conclude that C_l = 85.0 ± 1.0 percent carbon should adequately describe the mean composition of world crude oil during the period of interest here. Because natural gas liquids comprise only 3 percent of the total liquids, little error can be introduced by applying this factor to the sum of crude petroleum and natural gas liquids, as pointed out above.

Solids

As indicated earlier, the UN now attempts to evaluate coals and tabulates production in the energy units "tons coal equivalent" at 7000 cal/gm. The correlation between heating value and carbon content suggests that we can establish estimates for carbon content using the knowledge that the UN has considered the heating value in their published production data. That the correlation between heating value and carbon content is good but not perfect is seen clearly in attempts to write formulas for calculating heating value from chemical analyses. For example, one such attempt arrived at the formula:

$$\Delta H_H = 146.58C + 568.78H + 29.4S - 6.58A - 51.33(O + N) \qquad \text{Eq. 4}$$

where ΔH_H is the higher heating value in Btu/lb and C, H, S, A, and (O+N) are weight percents, respectively, of carbon, hydrogen, total sulfur, ash, and oxygen plus nitrogen by difference (all on a moisture-free basis). While this was the most successful of five published equations which were evaluated by the Institute for Gas Technology (1978), when calculated and measured values for 775 U.S. coals (including lignites and subbituminous coals) were compared, the average of the absolute value of the differences was 93 Btu/lb (52 cal/g). It is clear that whether the precise expression of Equation 4 is used, having the heating value of coal makes it possible to estimate the carbon content.

A higher heating value of 7000 cal/g is a reasonable standard for coal equivalents and until recently it was the standard employed in the UN data tabulations. To determine the factor C_s to be used in Equation 1, it is then necessary to establish the average carbon content of 7000 cal/g coal. Although the carbon content of solid fuels is variable, for 7000 cal/g coal close definition is possible. For the Zubovic et al. (1979) compilation of

coal analyses (mean heating value of 7090 cal/g) the arithmetic mean carbon content was 70.9 percent for the 491 samples for which ultimate analyses were available. These were samples with heating values varying from 4706 to 8307 cal/g and carbon content from 48.2 to 85.9 percent. For the 26 samples with heating values between 6900 and 7100 cal/g the mean heating value was 6997 kcal/kg and the mean carbon content 70.7 percent. "Coal equivalent" is thus assumed to contain 70.7 percent carbon. We suggest C_s = 70.7 percent carbon describes coal equivalent within ±2 percent, although it does appear that the carbon fraction per unit heating value increases slightly for low grade coals.

The higher heating value of coal is a commonly measured value and most of the discussion above has been based on higher heating value. However, in its most recent tabulations the UN has attempted to base coal equivalents on lower heating value ("net heat value" in their terminology) while staying with a 7000 cal/g basis. Therefore we must make some adjustment. To use the UN data set for coal production with coal composition information based on the higher heating value, the coal composition factor must include a multiplier which simultaneously converts tons of coal equivalent from a lower to a higher heating value basis. This factor is based on U.S. data and assumes only that the ratio of $\Delta H_H/\Delta H_L$ is the same for average world coal as for U.S. coal. Table 3 shows, by year, the ΔH_H of U.S. coals as reported by the U.S. Bureau of Mines and DOE and the heating value assumed by the UN in converting tons of U.S. coal to tons coal equivalent. By including a factor of $\Delta H_H/\Delta H_L$ in the multiplication we effectively revert to a 7000 cal/g ΔH_H basis, and this can be regarded simply as a heating value adjustment factor. It should be changed if the UN alters its accounting basis in the future.

From the heating values used by the UN in tabulating U.S. coal production in the 1980 Yearbook of World Energy Statistics (Table 3) the mean heating value adjustment factor for 1970-1979 data is found to be 1.055. We assume this factor is appropriate for world coal. Combining the composition and heating value adjustment factors, the effective carbon content of world average coal is found to be C_s = (0.707)(1.055) = 0.746 ± 0.02. We emphasize that this is uniquely appropriate for the UN coal statistics reported on a "net heat value" basis.

CALCULATION OF CO_2 EMISSIONS AND ESTIMATION OF ERROR

The computation of CO_2 emissions from fossil fuel burning is accomplished by multiplying the factors developed above and summarized in Table 13. The fuel data taken from the 1980 Yearbook of World Energy Statistics (UN, 1982) and the calculated values for CO_2 emissions are presented and summed in Table 14. (The 1981 fuel and CO_2 emissions are estimated from incomplete data for that year as compiled in UN quarterly reports.) A large number of assumptions and approximations are embodied in these computations but in every case the values are rather well bounded. We have tried to draw these approximations in such a way as to acknowledge the uncertainties but to show also that the results cannot lead to large errors in the calculation of CO_2 emissions.

Because liquids provide probably the worst case for accumulation of errors, assembling and contemplating all of the errors and approximations contained in the calculation of CO_2 emissions from liquids provides bounds for other fuels as well. Global production data can be used as a surrogate for annual consumption if identifiable nonoxidative uses are subtracted. Changes in stocks are small compared to production and, over a series of years, must contain positive and negative numbers summing to near zero. Assuming that crude oil and natural gas liquids could be summed on a mass basis introduces little error because of the demonstrated small difference in mean carbon content and the small contribution of NGLs to the total. Global fuel production numbers compiled by the United Nations are consistent with numbers published elsewhere and represent the best efforts of a staff dedicated to the sole task of bringing together all of the available information. All production data are subject to revision as additional information becomes available but ultimately all data depend on the reporting of individual nations and production companies. The error estimates for production data (± 8 percent for liquids) are judgments made after discussing global and some individual country data with the UN staff plus discussions with others more familiar with U.S. data.

The most speculative numbers in our computation are those that relate to how crude oil is ultimately used and the rate at which it is oxidized. It is absolutely clear, however, that over 90 percent of crude is used for

TABLE 13. FACTORS AND UNITS FOR CALCULATING ANNUAL CO_2 EMISSIONS FROM GLOBAL FUEL PRODUCTION DATA*

$$CO_{2_i} = (P_i)(FO_i)(C_i)$$

From Natural Gas Production

CO_{2_g} = CO_2 emissions in 10^6 tons C

P_g = Annual production in thousands of 10^{12} joules (± ≈ 10 %)

FO_g = Effective fraction oxidized in year of production = 0.98 ± 1%

C_g = Carbon content in 10^6 tons per thousand 10^{12} joules = 0.0137 ± 2%

From Crude Oil and Natural Gas Liquids Production

CO_{2_l} = CO_2 emissions in 10^6 tons C

P_l = Annual production in 10^6 tons (± ≈ 8%)

FO_l = Effective fraction oxidized in year of production = 0.918 ±3%

C_l = Carbon content in tons C per ton crude oil = 0.85 ±1%

From Coal Production

CO_{2_s} = CO_2 emissions in 10^6 tons C

P_s = Annual production in 10^6 tons coal equivalent (± ≈ 11.2%)

FO_s = Effective fraction oxidized in year of production = 0.982 ± 2%

C_s = Carbon content in tons C per ton coal equivalent = 0.746** ± 2%

From Natural Gas Flaring

CO_{2_f} = CO_2 emissions in 10^6 tons C

P_f = Annual gas flaring in 10^9 cubic meters (± ≈ 20%)

FO_f = Effective fraction oxidized in year of flaring = 1.00 ± 1%

C_f = Carbon content in tons per thousand cubic meters = 0.525 ± 3%

• All masses are in metric tons (10^3kg).

**The 0.746 value includes a heating value adjustment to recognize that the carbon content, developed on a higher heating value basis, must be increased when used with UN production data (UN, 1982) based on "net" or lower heating values.

TABLE 14. CO_2 EMISSIONS FROM FOSSIL FUELS, 1950-1981

Year	Gas Fuel Production[1] (10^{12} joules) (thousands)	CO_2 From Gas Fuel (10^6 T C)	Liquid Fuel Production[2] (10^6 T oil)	CO_2 From Liquid Fuel (10^6 T C)	Solid Fuel Production[3] (10^6 T coal eq)	CO_2 From Solid Fuel (10^6 T C)	Gas Flared & Vented[4] (10^9 m^3)	CO_2 From Flared Gas (10^6 T C)	Total CO_2 From Fossil Fuels (10^6 T C)
1950	7,193	97	542	423	1,468	1,075	44	23	1,618
1951	8,562	115	613	478	1,549	1,135	46	24	1,752
1952	9,241	124	646	504	1,534	1,124	50	26	1,778
1953	9,772	131	684	534	1,542	1,130	51	27	1,822
1954	10,250	137	714	557	1,528	1,119	52	27	1,840
1955	11,140	150	801	625	1,654	1,212	58	30	2,017
1956	12,027	161	870	679	1,743	1,277	61	32	2,149
1957	13,247	178	915	714	1,793	1,314	67	35	2,241
1958	14,296	192	938	732	1,829	1,340	66	35	2,299
1959	15,976	214	1,012	790	1,877	1,375	69	36	2,415
1960	17,501	235	1,089	850	1,946	1,426	75	39	2,550
1961	18,865	253	1,161	906	1,825	1,337	79	41	2,537
1962	20,592	276	1,258	982	1,868	1,368	84	44	2,670
1963	22,364	300	1,351	1,054	1,947	1,426	90	47	2,827
1964	24,447	328	1,458	1,138	2,018	1,478	97	51	2,995
1965	26,172	351	1,563	1,220	2,048	1,500	104	55	3,126
1966	28,313	380	1,696	1,323	2,077	1,522	115	60	3,285
1967	30,500	409	1,822	1,422	1,998	1,464	126	66	3,361
1968	33,130	445	1,988	1,551	2,040	1,494	139	73	3,563
1969	36,268	487	2,139	1,669	2,077	1,522	152	80	3,758
1970	38,441	516	2,350	1,834	2,152	1,576	167	88	4,014
1971	41,204	553	2,492	1,945	2,146	1,572	171	90	4,160
1972	43,391	583	2,632	2,054	2,163	1,585	180	95	4,317
1973	45,284	608	2,868	2,238	2,190	1,604	213	112	4,562
1974	45,897	616	2,877	2,245	2,202	1,613	204	107	4,581
1975	46,246	621	2,730	2,130	2,297	1,683	183	96	4,530
1976	48,043	645	2,958	2,308	2,357	1,727	210	110	4,790
1977	49,275	662	3,077	2,401	2,410	1,765	206	108	4,936
1978	51,525	692	3,107	2,424	2,438	1,786	201	106	5,008
1979	54,339	730	3,236	2,525	2,574	1,886	200	105	5,246
1980	55,056	739	3,093	2,413	2,615	1,916	194	102	5,170
1981[5]	58,118	780	2,878	2,246	2,650	1,941	178	93	5,060

Notes: Table 14

1. Data from 1980 Yearbook of World Energy Statistics, UN (1982), and Data Tape of UN Energy Statistics.

2. Data from 1980 Yearbook of World Energy Statistics, UN (1982), and Data Tape of UN Energy Statistics. Numbers are the sum of crude oil and natural gas liquids, both in mass units.

3. Data from Data Tape of UN Energy Statistics; 0.810 coal equivalency factor used for hard coal produced in Poland (in millions of tons of coal equivalent where coal equivalent means net heating value of 7,000 cal/gram).

4. 1950-70 data from Rotty (1974).
   1971, 1972 data from U.S. Department of Interior (1974).
   1973 data from U.S. Department of Energy (1979).
   1974-1978 data from U.S. Department of Energy (1980b).
   1979-1981 data are estimates by authors.

5. All 1981 production values are estimates based on midyear data.

The data tapes of UN Energy Statistics were employed with the assistance of J. E. Horwedel, Carbon Dioxide Information Center, Oak Ridge National Laboratory.

fuels that are burned within a short time of production and errors of only a few percent of total CO_2 emissions are possible as a result of accounting inadequacies within the fraction remaining unoxidized. The fraction not oxidized results from both nonfuel use and combustion inefficiencies. The assumption of 98.5 ± 1 percent oxidization effectively recognizes that CO and most unburned or partially oxidized hydrocarbons will soon be oxidized in the environment while soot will remain unoxidized for long periods of time. Although recognizing that we have committed errors of both omission and inclusion, we have listed a variety of nonfuel petroleum products that have long lifetimes before oxidation, and have assumed that the sum closely approximates the fraction of petroleum which is not oxidized each year. Recent year data suggest this is about 6.7 percent of production and we conclude that errors of greater than ± 2 percent of production are unlikely. One problem is that this fraction (and the combustion efficiency) are functions of time and place and we are forced to rely on recent U.S. data to infer long-term global averages. If the fraction of fuel going into long-lifetime products has been increasing over the last several decades, use of estimates of that fraction based on present data will result in CO_2 emissions that are slightly too low for earlier years. However this will be, at least partially, compensated by an increase in fuel combustion efficiency with time. The data cited above also suggest that nonfuel uses of coal and natural gas have been decreasing with time while average coal combustion efficiency has been increasing with time. Data are not available to try to discern quantitatively the effect of changing nonfuel uses and increasing combustion efficiencies on the growth rate of CO_2 emissions.

There are enough data published on the composition of world crudes, partly because so much of world crude enters into international commerce, that we can be quite confident in establishing its mean carbon content. Errors in the procedures and the calculations stemming from carbon content or from fracion oxidized are much smaller than those from fuel data.

With present global fuel data, error limits cannot be assigned with scientific precision, but rather the ● values indicated represent our subjective judgment for an approximate 90 percent confidence interval over distributions not unlike normal. This is distorted somewhat when we recognize that some of the factors used are dominated by data from the most

recent third of the data sequence and that time dependent biases have been introduced by employing constant multipliers for the entire 1950-1981 period. Working largely in energy units should suppress time-dependent, systematic errors in the fuel production and fuel composition data, but fuel combustion efficiency and nonfuel use have almost certainly undergone systematic changes not recognized in our calculation. Since these changes affect quantities which are of the order of a few percent and the quantities are then subtracted from unity, any adjustments can give only small changes in net CO_2 production or its rate of increase.

We have estimated the overall uncertainty associated with CO_2 emissions by the analysis depicted in Table 15. In 1980 the CO_2 emissions from each fuel group were divided as follows: 14 percent from natural gas, 47 percent from liquid fuels, 37 percent from solid fuels, and 2 percent from flaring gas. Using these percentages as weighting factors on the uncertainties for each fuel group, this analysis suggests that the estimates on the global total emissions of CO_2 from fossil fuels presented in Table 14 have an uncertainty of between 6 and 10 percent, depending on how one chooses to aggregate the uncertainties.

The uncertainty in the value used for fuel produced is independent of the uncertainty in the estimate for fraction oxidized and the estimated carbon content. The uncertainty in the product of the three terms is estimated by the square root of the sum of the squares of the uncertainty in each individual component. However, in summing the uncertainties for CO_2 emissions from each fuel type to obtain an overall uncertainty for global CO_2 emissions independence is not assured. If the data for each fuel type were totally independent, the square-root-of-the-sum-of-the-squares would be the appropriate procedure and the estimated uncertainty would be 6.06 percent. In at least a few cases, it is likely that data for gases, liquids and/or solids are developed and tabulated in the same office or even by the same individual and errors of the same type may occur in data for more than one fuel type. In this case compensating errors would not occur and the cumulative uncertainty could be as much as $\sum f_i \sqrt{\Sigma E_j^2}$, 10.16 percent in this case (see Table 15). The estimated uncertainty in the final emission numbers of between 6 and 10 percent is based on a 90 percent confidence interval.

TABLE 15. UNCERTAINTIES IN CO_2 EMISSIONS (%)

	E_1 Fuel Produced (P)	E_2 Fraction Oxidized (FO)	E_3 Carbon Content (C)	Emissions* $\sqrt{\Sigma E_j^2}$	Weighted** Emissions $f_i \sqrt{\Sigma E_j^2}$
Gases	10	1	2	10.25	1.47
Liquids	8	3	1	8.60	4.01
Solids	11.2	2	2	11.55	4.28
Gas Flared	20	1	3	20.25	0.41

Total Uncertainty:

a. If uncertainties for the individual fuels are mutually independent. $\left[\sum_i \left(f_i \sqrt{\Sigma E_j^2}\right)^2\right] = 6.06$

b. If uncertainties for the individual fuels are not independent. $\sum_i f_i \sqrt{\Sigma E_j^2} = 10.16$

* E_j is the uncertainty in the factors P, FO, and C for a given fuel type i.

** Weighted by 1980 weighting factor f_i = 1980 emissions from i th fuel type divided by total 1980 emissions.

The uncertainty of 6 to 10 percent is applicable to CO_2 emissions for a given year, but the uncertainty in the relative change from year to year is a different problem. Growth rates are determined by linear least squares fitting of the logarithms of the annual emissions and thus confidence in growth rates can be different from confidence in annual values. There is a memory component in the annual fuel data; that is, fuel production data for a given year are influenced by, and hence not totally independent of, the previous year's data. One of the checks employed by the UN is that reported production data must demonstrate continuity with the previous year's values. In addition, some time-dependent bias may be introduced by the calculative procedure used. However, if we assume that there is a constant exponential growth in CO_2 emissions for a particular period, then we can use some simple statistics to estimate confidence limits on the annual growth rate. Assuming that the yearly emissions are independent, and that the statistical deviation from constant exponential growth is the same as the statistical deviation in the individual annual emissions, and that ± 8 percent is the 90 percent confidence bound on individual values we calculate that the annual growth rate for the period 1950-1973 is 4.46 ± 0.24 percent. For the period 1973-1981 it is 1.86 ± 1.13 percent.

Because of the memory in the data system, data precision can be much greater than data accuracy; the uncertainty in individual values is not reflected in the difference between successive annual values. Thus, in determining year to year differences, using annual values calculated to four significant figures is not inappropriate.

To reduce the uncertainty in the final result would require that the reliability (or confidence in) the fuel production data be substantially improved. It is shown clearly in Table 15 that most of the uncertainty in calculating CO_2 emissions from fossil fuels comes directly from this source. Developing improved confidence in the UN fuel statistics for even that small group of countries that produce most of the world's fuel, would require a major effort.

We have made no attempt to examine CO_2 emissions prior to 1950. Estimates of Keeling (1973) remain the only source extending back to 1860. There is virtually no difference between the results presented here for the early 1950's and Keeling's values for the same period (e.g., 1618 x 10^6 tons

C for 1950 calculated here compares with 1613 x 10^6 tons carbon calculated by Keeling). Although this apparent agreement makes it easy to combine data for the two periods into a single sequence, we caution that the two series have been developed by different methods from data sets having different uncertainties.

The only other significant contribution of CO_2 emissions from industrial activities appears to be related to cement manufacture. Cement production contributes about 2 percent additional to the total CO_2 emissions. Cement data have not been reexamined here and for a complete data set of industrial CO_2 releases, cement data from Rotty (1982) should be added to the fossil fuel data derived here.

CONCLUSIONS

An important outcome of this exercise is that an independent examination of the full computation of CO_2 emissions from fossil fuels has been completed and no fundamental oversights in the earlier methods of Keeling and of Rotty have been found. Differences from the earlier results are minor, well within the uncertainty limits in the data available. At the same time we emphasize the uncertainties in the results, and any effort toward a global carbon balance should acknowledge that CO_2 production numbers reported to three or four significant figures are nonetheless subject to substantial uncertainty.

The CO_2 emissions given in Table 14 are displayed in Figures 5 and 6. Figure 5 shows graphically the rate at which CO_2 emissions have been growing and the relative contributions of the various fuels. This figure shows the early dominance of the emissions from coal and the rapid increase in emissions from liquids between 1950 and the early 1970s. The disruption of the growth in emissions that accompanied the dramatic change in energy prices and availability beginning in 1973 is clearly evident and appears to be mostly a consequence of reduced use of oil and gas.

In Figure 6 the percentages shown are average exponential growth rates calculated by linear least squares fitting of the logarithms of the annual emissions. Although the trends indicated in Figure 6 for the period following 1973 are based on only nine points and hence are susceptible to some adjustment as additional years are added to the data, the change in growth rates around 1973 is quite evident. The pre-1973 4.5 percent annual rate of growth in CO_2 emissions from all fossil fuels has been reduced to less than half that. Carbon dioxide emissions from oil and gas show the 1973 change even more clearly. The apparent small increase shown in the growth rate in coal production following 1973 must be considered in terms of the relatively short period over which the 2.57 percent annual rate was determined. The basic change in total fossil fuel use that occurred in 1973 could be quite important. Rates of growth of CO_2 emissions that were occurring with "cheap energy" are unlikely in the near future.

Although the estimated uncertainty in the CO_2 emissions is about 10 percent, the trend of increasing emissions from fossil fuels is firmly

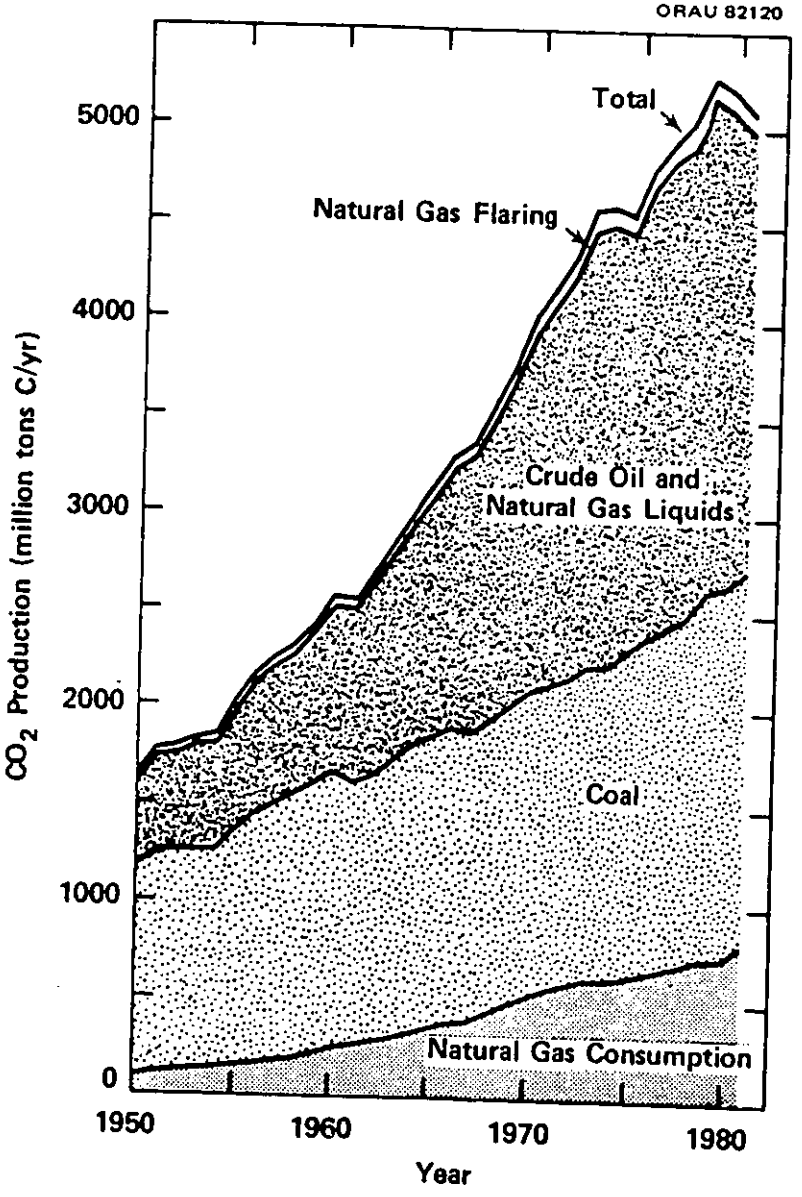

Figure 5. Annual CO_2 production from fossil fuel burning, 1950–1981.

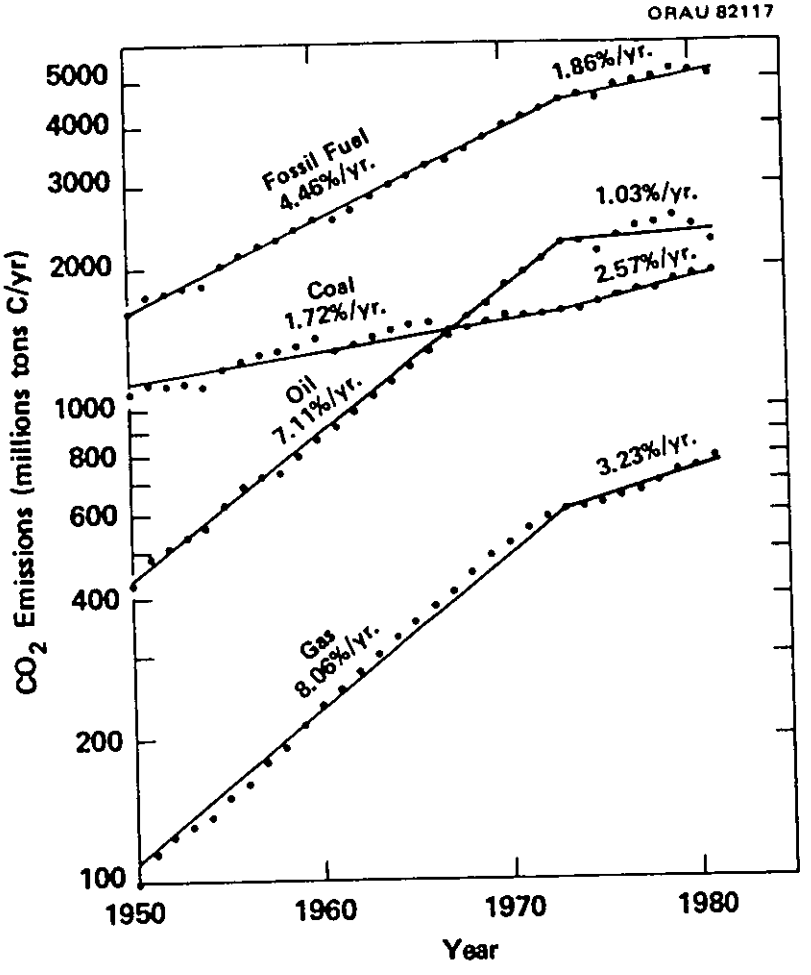

Figure 6. Annual CO_2 Production from Each Fossil Fuel Group and Total Fossil Fuels.

established. There may be a small time-dependent error in the emissions calculation but the 1950-1973 annual growth rate cannot be far from the 4.5 percent per year calculated here and, although not yet well defined, the growth rate following 1973 is about half the earlier rate. Even prior to the 1981-82 recession (during which the emissions actually decreased for two consecutive years) the reduced growth rate was clearly evident.

ACKNOWLEDGMENTS

This report was prepared under contract number DE-AC05-760R00033 between the U.S. Department of Energy, Office of Basic Energy Sciences, and Oak Ridge Associated Universities. Much of the analysis of the fuel data, the fraction remaining unoxidized, and the carbon content was done during the period 1980-82 under contract between the Gas Research Institute and Oak Ridge Associated Universities, and the inputs from that work to this report are substantial.

We are indebted to William Clive and his staff of the Energy Statistics Branch of the United Nations Department of International Economic and Social Affairs and to J. E. Horwedel of the Carbon Dioxide Information Center, Oak Ridge National Laboratory for their assistance with the world energy data. We also appreciate the suggestions of C. D. Keeling, A. M. Perry, W. P. Elliott and several other reviewers and the help of N. Mynatt and E. Ayres in the preparation of the manuscript.

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