# Reports

## Industrial Emissions of Carbon Dioxide in the United States: A Projection

Abstract. *Carbon dioxide builds up in the earth's atmosphere principally from increased use of fossil fuels. Estimates of the escalating uses of fossil fuels in the United States, especially for the generation of electric power and in the internal combustion engine, show that by the year 2000 emissions will have increased approximately eighteenfold from 1890. In the period 1965 to 1985 an emission-rate increase of around 4.0 percent per year compounded is expected. The expected intrusion and expansion of nuclear power will tend to lower the rates of increase of emission after 1985. Increases in emission rates in the rest of the world will probably equal or exceed the values projected for the United States.*

Carbon dioxide emissions retained in the atmosphere have received particular interest from several national organizations (*1*). Chamberlain (*2*) as early as 1899, and Arrhenius (*3*) in 1903, as well as Callendar (*4*) in 1938, suggested that the combustion of fossil fuels might add abnormal amounts of carbon dioxide to the atmosphere which could influence the atmosphere's temperature. Carbon dioxide is a strong absorber and back radiator of infrared radiation. A buildup of carbon dioxide could then produce a "greenhouse effect" and encourage a warming trend over the years.

Minor effects of the increasing emission of carbon dioxide might contribute slight increases of acidity to the waters of the earth because of the combination of carbon dioxide and water to form carbonic acid (*5*).

Industrial sources of carbon dioxide can be attributed largely to the combustion of fossil fuels and the manufacture of cement. The flow of fossil fuels into various combustion processes must be considered for reasonable projections of carbon dioxide emissions. The escalating demands for coal and oil for power plant combustion together with the lowered rate of the demands by railroads and by retail and industrial users call for a careful scrutiny of possible future consumption. The use of cement and many petroleum products can be projected by association with expected growth of both population and the Gross National Product.

For the purposes of this analysis, we have assumed that the average coal will contain 75 percent carbon, the average crude oil 80 percent carbon, and the average natural gas 73 percent carbon. We have also assumed that 90 percent of the crude oil and natural gas production will end up as combustion products and that the remaining 10 percent will be lost as liquid and vapor or converted to fixed carbon products not burned.

Briefly, the use of coal and oil by power plants is expected to increase 8.5 percent per year plus increments of 0.1 percent a year to 1970, yearly decrements of 0.1 to 0.4 percent to 1980, and more accelerated decrements to 1990 (*6*). We expect that nuclear power will gradually, and then more rapidly, take over large portions of steam generation the latter part of this century.

The use of coal for other purposes that will eventually form carbon dioxide is expected to decrease at a 2 percent yearly rate. Other oil use and eventual combustion will increase at a 3 percent yearly compounded rate (*7*). The replacement of internal combustion engine power for vehicles by battery power sources (which would be recharged from power-generating plants) has not been considered. The results of this change in technology, if adequate rechargeable-battery power sources do become available, would not be significant as far as carbon dioxide emissions are concerned until after about 1990. If such a development can become practicable, emissions of carbon dioxide would decrease after the turn of the century, reflecting the take-over of fossil fuel power for vehicles by electric power generated by atomic fuels. The use of fuel cells operating on hydrocarbon fuels would not affect significantly the carbon dioxide emissions from vehicles. The burning of natural gas will increase 6 percent per year, plus increments of 0.1 percent to 1970 followed by decrements of 0.1 percent after 1971 to 1975, and variable decrements later to reflect the influence of nuclear power gradually taking over power generated by natural gas. The "burning" of limestone will increase 4 percent per year.

Carbon dioxide is present in most natural gas and is also emitted from many oil wells; however, the total amounts from these sources, while appreciable, are not large enough to influence these data. All data are shown in Table 1 and Fig. 1.

Table 1. Major industrial sources of carbon dioxide (ton × $10^6$) emitting to the U.S. atmosphere.

| Year | Power plants | | | Other combustion | | | Total fossil fuel | Cement manufacture | Total $CO_2$ emissions | From power plants (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coal | Oil | Gas | Coal | Oil | Gas | | | | |
| 1890 | 10 | 1 | 0 | 356 | 21 | 1 | 388 | 2 | 422 | 2 |
| 1900 | 12 | 1 | 0 | 510 | 34 | 9 | 555 | 4 | 559 | 2 |
| 1910 | 25 | 1 | 1 | 960 | 118 | 28 | 1163 | 7 | 1170 | 2 |
| 1920 | 77 | 3 | 5 | 1191 | 204 | 66 | 1546 | 13 | 1559 | 5 |
| 1930 | 96 | 4 | 8 | 1023 | 485 | 99 | 1715 | 16 | 1731 | 6 |
| 1940 | 176 | 8 | 11 | 970 | 614 | 154 | 1933 | 18 | 1951 | 10 |
| 1945 | 183 | 11 | 20 | 1209 | 792 | 201 | 2416 | 14 | 2430 | 9 |
| 1950 | 217 | 38 | 39 | 910 | 1089 | 307 | 2600 | 33 | 2633 | 11 |
| 1955 | 340 | 38 | 68 | 706 | 1223 | 486 | 2861 | 43 | 2904 | 15 |
| 1960 | 418 | 43 | 101 | 509 | 1400 | 589 | 3060 | 48 | 3108 | 18 |
| 1965 | 673 | 59 | 134 | 495 | 1510 | 669 | 3540 | 55 | 3595 | 24 |
| 1970 | 1031 | 92 | 150 | 448 | 1751 | 870 | 4342 | 69 | 4411 | 29 |
| 1975 | 1510 | 108 | 160 | 405 | 2028 | 998 | 5209 | 82 | 5291 | 34 |
| 1980 | 2060 | 203 | 160 | 366 | 2353 | 1131 | 6273 | 99 | 6372 | 38 |
| 1990 | 2403 | 277 | 155 | 300 | 3162 | 1392 | 7689 | 146 | 7835 | 36 |
| 2000 | 2197 | 254 | 150 | 245 | 4252 | 2227 | 9325 | 216 | 9541 | 37 |

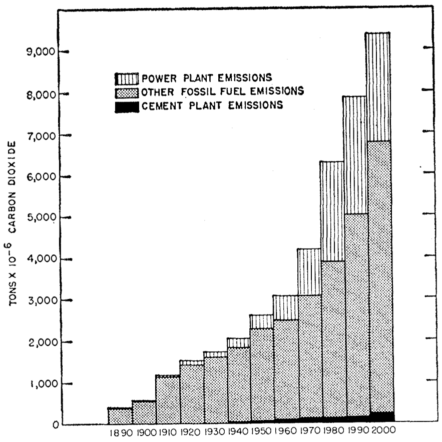

Fig. 1. Carbon dioxide emissions from power plant and other industrial operations.

Carbon dioxide emissions from industrial sources should project to approximately eighteenfold from 1890 to 2000. The greatest average increases in rates of carbon dioxide emissions will be about 4 percent per year and will occur between 1965 and 1985. This is the period when increased demands on fossil fuels for power generation will be the greatest and when nuclear power generation will be proved.

In the absence of more precise and definitive data from other countries one can only speculate on the increases in worldwide emission rate of carbon dioxide. It seems reasonable that emission rates in many other presently industrialized areas will be similar to those in the United States, and that in a large share of the world, particularly the underdeveloped regions, emissions will increase at even greater rates because these regions possess the latent urge and potential for greater industrialization and progress.

F. A. Rohrman
B. J. Steigerwald
J. H. Ludwig
*National Center for Air Pollution Control, U.S. Public Health Service, Cincinnati, Ohio*

**References**

1. *Implications of the Rising Carbon Dioxide Content of the Atmosphere* (The Conservation Foundation, New York, 1963); Report of the Environmental Pollution Panel, President's Science Advisory Committee, 1965, p. 111.
2. T. C. Chamberlain, *J. Geol.* **7**, 575 (1899).
3. Svante Arrhenius, *Lehrbuch der Kosmischen Physik* (Hirzel, Leipzig, 1903), vol. 2.
4. G. S. Callendar, *Quart. J. Roy. Meteorol. Soc.* **64**, 223 (1938).
5. F. A. Rohrman and J. H. Ludwig, *Chem. Eng. Progr.* **61**, 59 (1965).
6. F. A. Rohrman, B. J. Steigerwald, J. H. Ludwig, paper presented to Amer. Soc. Mech. Eng.–Inst. Elect. Electron. Eng. National Power Conference, Albany, N.Y., Sept. 1965.
7. Staff Study, *Oil Gas J.* **63**, 95 (1965).

6 February 1967; 3 April 1967

---

# Ionium Dating of Igneous Rocks

Abstract. *Local fractionation of uranium and thorium, between minerals within a sample of igneous rock at the time of crystallization, makes it possible to date its solidification by use of ionium and uranium. Results on samples of granite, pumice, and lava suggest that this method of dating is reliable.*

Much chronological information on Quaternary events has derived from use, in dating, of the radioactive disequilibrium between ionium and uranium in pelagic sediments (*1*) and marine biologic carbonates (*2*). From carbonates, ionium was essentially excluded at the time of formation, and the observed approach to equilibrium makes it possible to date the time of formation. I now extend the application of ionium dating to igneous rocks, which almost always have had amounts of ionium in equilibrium with uranium since the time of their solidification.

In a rock that is not very old in comparison with the half-life of ionium, some of the ionium has been contained since the time of solidification; the remainder has grown *in situ* from $U^{234}$ after the solidification. The ratio of these two amounts of ionium from different genetic origins varies in each mineral according to its uranium and thorium contents. The amount of accumulated ionium must be proportional to the amount of $U^{234}$ or $Th^{234}$ in each mineral, and the amount of original ionium that has survived since the time of solidification must be proportional to the amount of $Th^{232}$. With this expected regularity in the distribution of thorium isotopes in different parts or minerals of an igneous rock, we can determine the amounts of the two kinds of ionium, from which we can date solidification of the rock.

If thorium isotopes are completely mixed in a rock at the time it crystallizes, and if a phase or a mineral of the rock sample has been kept as a closed system for $t$ years after solidification, the total amount of $Th^{230}$ in this part is given by

$$A_{0i} = aA_{2i}\exp(-\lambda t) + A_{4i}[1-\exp(-\lambda t)] \quad (1)$$

where $A_{0i}$, $A_{2i}$, and $A_{4i}$ are the disintegration rates of $Th^{230}$, $Th^{232}$, and $Th^{234}$, respectively, in a phase indicated by subscript $i$; $a$ is an activity ratio $A_{0i} : A_{2i}$, at $t = 0$, which must be constant in all phases of a rock sample; and $\lambda$ is the decay constant of $Th^{230}$. The first term of Eq. 1 indicates a decrease of the ionium that has been included, with $Th^{232}$, in the $i$-th phase of the rock sample since the time of solidification; the second term indicates increase of the ionium from $U^{234}$. By use of the ratios $R_{0i} = A_{0i} : A_{2i}$ and $R_{4i} = A_{4i} : A_{2i}$ for two different parts ($i$ and $j$) of a rock sample, Eq. 1 gives an age of solidification ($t$) as

$$t = \frac{1}{\lambda}\ln\left[1/\left(1 - \frac{R_{0i} - R_{0j}}{R_{4i} - R_{4j}}\right)\right] \quad (2)$$

The precision of this method of dating depends mainly on the magnitude of the difference ($R_{4i}-R_{4j}$) arising from the fractionation of uranium and thorium in the phases $i$ and $j$.

Instead of mechanical or dynamic separation of minerals, partial dissolution or extraction may be used to separate the portions having different ratios of uranium:thorium. I now report some results of analyses of portions separated by heavy liquids or acid treatment. The following acid treatments yield two portions: (i) boiling 20- to 200-gram samples of powdered rock in 2*N* HCl for 40 hours, and (ii) solution in 9*N* HF of most nonmafic minerals in the residues remaining from the treatment with HCl. In Table 1, G-1 and O-1 correspond to the HCl-extracted solutions, and G-2 and O-2 correspond to HF-dissolved portions. A-1 is a portion obtained by partial dissolution of the powdered rock by 9*N* HF without any pretreatment, and A-2 is a residue from the HF treatment that mainly consisted of mafic minerals. Separation of heavy liquid (Toulet solution) gave two portions: O-4, consisting mainly of glass, and O-3, consisting of mafic minerals.

The thorium in these separated portions was purified by mesityl oxide extraction, fluoride precipitation, and ex-

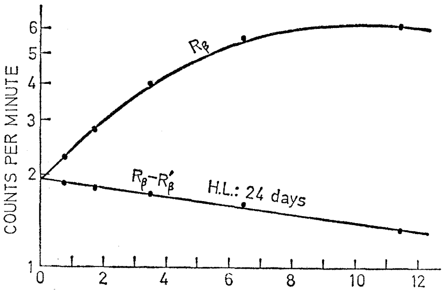

Fig. 1. Semilog plot illustrating the increase in observed beta activity ($R_\beta$) and decay in $Th^{234}$ activity that were obtained from $R_\beta - R_\beta'$. *H.L.*, half-life.