

APPENDIX D

PHYSICS OF SOME ENVIRONMENTAL ASPECTS OF ENERGY

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ABSTRACT

Approximate numerical estimates are carried out on the following environmental effects from energy production and conservation: (1) The greenhouse effect caused by increased CO_2 in the atmosphere; (2) Loss of coolant accidents in nuclear reactors; (3) Increased radon concentrations in buildings with very low air infiltration rates; (4) Acid rain from the combustion of fossil fuels; and (5) Explosions of liquified natural gas (LNG).

INTRODUCTION

Enhanced end-use efficiency of energy not only conserves natural resources, but it also lessens the environmental impacts of obtaining those resources. We describe here some simplified models by which one can understand the basic physics principles of some of these environmental impacts. Our calculations of these environmental impacts have used only widely accepted numerical parameters, and the results agree with either direct observations or with more complex¹ calculations. We have considered the following environmental effects:

I. CO_2 . The present rate of increase of CO_2 (ppm/y) will be estimated. This result will be extrapolated to the middle of the last century and to the middle of the next century under various conditions. Market penetration of noncarbon technologies will be considered.

II. NUCLEAR. The time available after a loss of coolant accident for an emergency core cooling system to react will be estimated for a light water reactor (LWR) and for a high temperature gas reactor (HTGR). The case of a total loss of electrical power will be considered.

III. RADON. The energy available from reducing infiltration leaks will be estimated as well as the associated health effects.

IV. ACID RAIN. The approximate pH of the nation's rain will be estimated. Plumes from power plants, scrubbing, and pollution scaling laws will be considered.

V. LNG. The thermal energy and power from an LNG explosion will be calculated.

I: ATMOSPHERIC CO₂ (THE "GREENHOUSE" EFFECT).

The concentration of CO₂ in the atmosphere^{2,3} has risen from about 295 ppm in 1860 to about 345 ppm in 1984. Many scientists have predicted that a doubling of the CO₂ concentration will raise the average temperature of the earth by about 3°C (1.5°C at the equator and 4.5°C at the poles). (This temperature rise is not strictly caused by a "greenhouse" effect since actual greenhouses block convective heat transfer and the atmosphere does not do this.) The planet Venus is an extreme example of this effect; its thick CO₂ atmosphere (about 90 times the earth's atmospheric pressure with a CO₂ concentration of about 96%) causes a surface temperature of about 482°C. This logarithmical rise in temperature could drastically effect the earth's food supplies and flood the low regions of the earth. It is generally believed that the cause of the increase in CO₂ is primarily due to the burning of fossil fuels. On a heating basis, coal produces 24% more CO₂ than oil, and 76% more CO₂ than natural gas. Deforestation, thus far, seems to have exacerbated the problem, but has not been the main cause of the increase in CO₂.

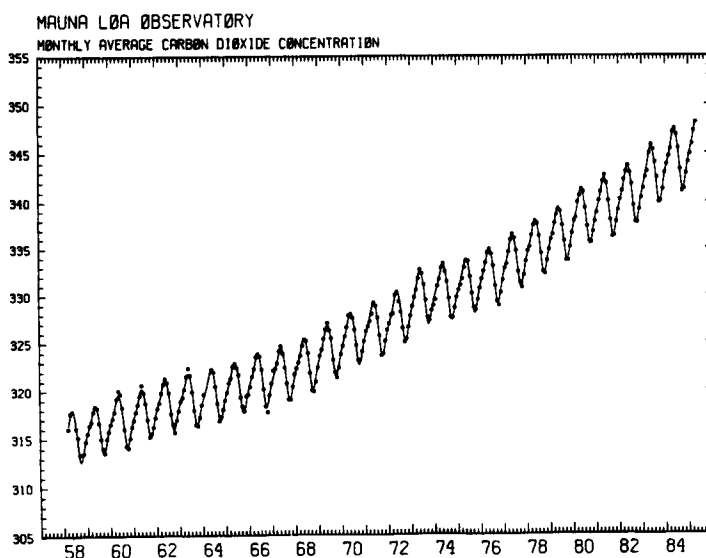


FIGURE 1. Concentration of atmospheric carbon dioxide observed with a continuously recording, non-dispersive infrared gas analyzer at Mauna Loa Observatory, Hawaii. The smooth curve represents a fit of the data to a four harmonic annual cycle which increases linearly with time, and a spline fit of the interannual component of the variation. The dots indicate monthly average concentrations. Data courtesy of C.D. Keeling, R.B. Bacastow, and T.P. Whorf, reference 3.

1.A. CO₂ GROWTH. Let us estimate the approximate deposition rate of CO₂ into the atmosphere and compare it to the current (1984) annual rise of about 1.5 ppm/year (by volume). The U.S. consumes about 35 million barrels per day (Mb/d) of petroleum equivalent which is about 30% of the world's consumption. The mass of fossil fuel burned each year on the earth is about

$$(35/0.3 \times 10^6 \text{ Mb/d})(365 \text{ d/y})(125 \text{ kg/b}) = 5.3 \times 10^{12} \text{ kg/y.}$$

About 80% of this amount is carbon, corresponding to

$$(0.8)(5.3 \times 10^{15} \text{ g})/(12 \text{ MolWt}) = 0.35 \times 10^{15} \text{ moles/y,}$$

of carbon, or about

$$(0.35 \times 10^{15})(6.023 \times 10^{23}) = 2.1 \times 10^{38} \text{ molecules/y}$$

of CO₂. Since the atmospheric pressure is about 10^5 Pascals, the total mass of the atmosphere is about

$$F/g = (10^5 \text{ Pascals})(4\pi)(6.4 \times 10^6 \text{ m})^2/(9.8 \text{ m/s}^2) = 5.3 \times 10^{18} \text{ kg}$$

which corresponds to

$$(5.3 \times 10^{21} \text{ g})(6.023 \times 10^{23})/(29 \text{ MolWt}) = 1.1 \times 10^{44} \text{ molecules}$$

in the entire atmosphere. It follows that the increase in CO₂ per year is $(2.1 \times 10^{38})/(1.1 \times 10^{44}) = 1.9 \text{ ppm/year}$ (by volume). This value is about 30% more than the measured increase of CO₂ of 1.5 ppm/y. This difference is often attributed to the absorption of the CO₂ by the oceans, although there is a large and, as yet, uncertain sink somewhere in the carbon cycle.

1.B. CO₂ BEFORE INDUSTRIALIZATION. By using the historic growth rate of 4.3%/year for fossil fuels prior to the oil embargo of 1973, we can estimate the CO₂ concentration in the atmosphere at the beginning of the industrial revolution. By integrating the 1.5 ppm/year backwards in time with the historic 4.3%/year growth rate, we obtain

$$\int_{-\infty}^0 (1.5 \text{ ppm/y})(e^{0.043t})dt = 35 \text{ ppm}$$

for the increase in CO₂ from the industrial revolution. By subtracting this value from the value of 345 ppm in 1984, we obtain 310 ppm for the CO₂ level prior to the industrial revolution. This is in good agreement with the often quoted value of 295 ppm.

1.C. THE CO₂ LEVEL IN THE YEAR 2050. By integrating forward in time from 1984 to 2050 we can obtain the CO₂ level in the year 2050. By assuming a 2%/year growth rate, we obtain

$${}^{66}\int_0 (1.5 \text{ ppm/y})(e^{0.02t})dt + 345 \text{ ppm} = 551 \text{ ppm}.$$

For other growth rates we obtain 444 ppm (0%/y), 485 ppm (1%), 657 ppm (3%), and 833 ppm (4%) respectively. Thus, it seems clear that the CO₂ level will double during the middle of the next century if carbon consumption continues to grow at 2 to 4%/year. The lower growth rates of 0 and 1%/y would markedly reduce the "greenhouse" effect.

1.D. THE RISE OF THE OCEANS. If the temperature increase caused by the increase in CO₂ is amplified in the polar regions to about a 5°C increase, the polar icecaps would partially disintegrate. It might take from decades to centuries for an ice shelf to disintegrate. Let us estimate how much the oceans would rise above if we initially assume that only the West Antarctic Ice Shelf is dislodged? The West Antarctica Ice Sheet, formed only 10 million years ago, has an area of about 1.5 million km² with an average thickness of about 1.5 km. The volume of water from the ice shelf is (1.5 × 10⁶ km²)(1.5 km)(0.9 water/ice) = 2.0 × 10⁶ km³. Spreading this volume over the area of the oceans (70% of the earth) gives a rise in the height of the oceans of

$$(2.0 \times 10^6 \text{ km}^3)/(0.7)(4\pi)(6400 \text{ km})^2 = 6 \text{ meters}.$$

This rise in the level of the oceans would cover about 2% of the U.S., and about 30% of Florida and Louisiana. Since it is generally believed that the temperature difference between glacial and interglacial periods is about 5°C, the rising of the oceans to flood the world's low lands is a distinct possibility. The complete disintegration of the Antarctica and Greenland ice would take much longer and is much less likely, but that event would raise the world's oceans by about 100 meters.

1.E. MARKET PENETRATION BY ALTERNATIVE TECHNOLOGIES. Assume that the fraction, f , of the energy market based on noncarbon technologies (sun, wind, nuclear, geothermal, conservation, the capturing of CO₂ and releasing it deep in the ocean, etc.) is able to increase linearly according to the relation $f = t/P$ where P is the time period for total market penetration. Let us estimate the ultimate CO₂ concentration in the atmosphere by the year 2050 ($P = 66$ y) assuming growth rates of 0 to 4%/y. In order to simplify the calculation assume that the lifetime of the additional CO₂ in the atmosphere is considerably longer than 66 years. The CO₂ concentration in the atmosphere is

$${}^P\int_0 (1.5 \text{ ppm})(e^{at})(1 - t/P) dt + 345 \text{ ppm}$$

where a is the energy growth rate. This integrates to

$$(1.5 \text{ ppm/Pa}^2)(e^{aP} - 1 - aP) + 345 \quad .$$

Using $P = 66$ years, we obtain CO_2 levels of 395 ppm (0%), 407 ppm (1%), 426 ppm (2%), 453 ppm (3%), and 492 (4%). These values are considerably lower than those quoted in Section I.C and they are consistent with those obtained by Laurmann⁴ who used a more complicated function to describe market penetration.

I.F. THE EFFECTS OF SYNFUELS AND NUCLEAR ENERGY. At one point the synfuel industry might have produced 5 Mb/d by the turn of the century. On the basis of delivered energy, synfuels will produce about 40% more CO_2 than burning coal, 70% more CO_2 than burning oil, and about 130% more CO_2 than burning natural gas. The use of energy in the world would rise to 135 to 150 Mb/d at the turn of the century with growth rates of 1 to 2%/y. Since this is considerably larger than the additional contributions of CO_2 from a large synfuels program (perhaps 5 Mb/d), the near term synfuels program wouldn't have mattered too much. However, a very large, world-wide synfuel industry in the future would complicate matters in the long term. At present nuclear power contributes about 2.5 Mb/d on a world wide basis, and it might contribute 5 to 10 Mb/d in the future. However, since nuclear power presently is only useful for (base-loaded) electricity which is 25% of the world's primary energy budget, it is not clear that nuclear power alone can save us from CO_2 .

II: LOSS OF COOLANT ACCIDENTS.

If a nuclear reactor loses its coolant and the emergency core coolant system (ECCS) fails to operate in the worst possible combination of circumstances, the reactor core could melt through the steel reactor vessel and then into the earth. The heat energy for a melt down comes mainly from the beta decay of the fission fragments in the core. It is also possible to melt the core of a reactor if all the electrical power systems for the reactor fail.

II.A. THERMAL RISE TIME IN A PWR AFTER A LOCA. Consider the case of a loss of coolant accident (LOCA) in a pressurized water reactor⁵ (PWR). Assume that the large amounts of water in the accumulator do not enter the reactor vessel until after the fuel rods have become quite hot. Let us estimate how long will it take the fuel of a PWR to rise to a temperature of 1370°C (2500°F) at which rapid damage to the core will begin to take place from the exothermic reaction of zircalloy and the water that comes from the accumulator. (UO_2 melts at 2200°C .) Assume the following: (1) The mass of UO_2 in a 1 GWe reactor is about 10^5 kg ; (2) The thermal efficiency of a PWR is about $1/3$; (3) The average temperature of the fuel is about 400°C before the LOCA; and (4) The thermal power after the LOCA is⁶

$$P = P_0(0.0766)(t^{-0.181}) \quad \text{for } t < 150 \text{ sec,}$$

and

$$P = P_0 (0.130)(t)^{-0.283} \quad \text{for } 150 \text{ sec} < t < 4 \times 10^6 \text{ sec},$$

where P_0 is the thermal power of the reactor before the LOCA, and t is the time in seconds after the LOCA. The rise time of the temperature after the LOCA is obtained by equating the heat necessary to heat the core to 1370°C to the integral over time of the thermal power P . The heat needed to raise the core is $Q = NC(\Delta T)$ where N is the number of moles, C is the molal specific heat of UO_2 , and ΔT is the temperature rise of the core ($1370^\circ\text{C} - 400^\circ\text{C} = 970^\circ\text{C}$). The number of moles of UO_2 in the core is about

$$N = (10^8 \text{ g}) / (238 + 32)(\text{g/mole}) = 3.7 \times 10^5 \text{ moles}.$$

Since 600°C is above the Debye temperature of UO_2 , we can use the high temperature specific heat, $C = 3R = 24.9 \text{ Joules/mole-}^\circ\text{C}$. It follows that the necessary heat to raise zircalloy to 1370°C

$$Q = NC(\Delta T) = (3.7 \times 10^5)(24.9)(970) = 8.9 \times 10^9 \text{ J}.$$

Since a 1 GWe (electric) reactor has a thermal power of 3 GWt (thermal), the rise time of the LOCA is obtained from

$$\begin{aligned} Q &= \int_0^t P \, dt = \int_0^t (0.0766)(3 \times 10^9)(t)^{-0.181} \, dt \\ &= (2.8 \times 10^8)(t)^{0.819} \text{ J} = 8.9 \times 10^9 \text{ J}. \end{aligned}$$

Solving this equation we obtain $t = 68$ seconds which is very close to the published values of about one minute from more sophisticated calculations using the parabolic heat equation.

11.B. THERMAL RISE TIME IN A HTGR AFTER A LOCA. The high temperature gas reactor⁷ (HTGR) uses graphite as a moderator and helium gas as a coolant in contrast to the PWR which uses light water as both a moderator and a coolant. As an interesting comparison let us calculate the thermal rise time for a HTGR after a LOCA in which the ECCS fails, using the following assumptions: (1) The heat capacity of the core of a HTGR is determined mainly by its 500,000 kg of graphite; the graphite reflectors and the nuclear fuel may be ignored; (2) The thermal efficiency of an HTGR is about 39%; (3) The average temperature of the core is about 750°C ; and (4) The core of an HTGR should be kept below about 1700°C .

The HTGR will have a considerably longer thermal rise time because its core has about 100 times greater thermal mass (the number of moles times the specific heat) than the core of a PWR. This follows because the mass of the HTGR core is about 5 times greater ($5 \times 10^5 \text{ kg}/10^5 \text{ kg}$), and because the molecular weight of graphite is

about 20 times smaller than UO_2 ($270/12 = 22$). In addition the rise time of the HTGR will be further lengthened because the HTGR can withstand higher temperatures (1700°C vs. 1370°C for the PWR). The heat necessary to heat the HTGR core to 1700°C is

$$Q = NC(\Delta T) = (5 \times 10^8/12)(24.9)(1700 - 750) = 9.9 \times 10^{11} \text{ J} .$$

This value of Q is 140 times larger than the PWR value because of the large heat capacity (mass times specific heat) of the core of the HTGR. By integrating the radioactive heat (before and after 150 sec), we obtain

$$Q = (10^9 \text{ W}/0.39) \left\{ \int_0^{150} (0.0766)(t^{-0.181}) dt + \int_{150}^t (0.13)(t^{-0.283}) dt \right\} \\ = (10^9 \text{ J}) \{ (0.46)(t^{0.717}) - 2.3 \} = 9.9 \times 10^{11} \text{ J} .$$

From this we obtain $t = 12$ hours which closely agrees with the value of about 10 hours obtained from more sophisticated calculations.

II.C LOCA FROM THE LOSS OF ALL ELECTRICAL POWER. The fire at the Brown's Ferry boiling water reactor (BWR) in Alabama shut down all the electrical power necessary for cooling the core. This could have resulted in a LOCA since the cooling water was evaporated by the heating from the residual radioactive fission fragments. Let us estimate how long would it take for the core to become uncovered under the following assumptions: (1) About 700,000 kg of cooling water must be evaporated for the core to become uncovered; and (2) Assume that only the usual heat of vaporization of water must be considered, 2270 J/g.

The amount of heat needed to evaporate the water is about

$$Q = (7 \times 10^8 \text{ g})(2270 \text{ J/g}) = 1.6 \times 10^{12} \text{ J} .$$

Setting this value of Q equal to the integrated radioactive heat for the PWR (which is about the same for the BWR) from II.B (with an efficiency of 0.33), we obtain $t = 19$ hours which was similar to the amount of time, about 13 hours, for the operator at Brown's Ferry to recover the situation and turn on the back-up pump.

III: INDOOR RADON.

The average level of radioactive radon in buildings⁸ is about 1 picoCurie/liter ($1 \text{ pCi/l} = 1 \text{ nCi/m}^3$). This value is about 5 times the corresponding outdoor background level of about 0.2 pCi/l. Considerably higher levels of radon as high as 25 pCi/l have been measured in houses. Radon-222 results from the decay of radium-226 which is part of the uranium-238 decay chain; the radon enters the building through the foundations, and from the building materials and the water supply. The level of radon in these buildings is directly

affected by the infiltration rate of fresh air from the outside since the fresh air replaces the inside air which contains radon-222 ($T_{1/2} = 3.8$ days). The principal health risk from radon-222 arises from the fact that the four radioactive daughters are not chemically inert and can attach themselves to airborne particulates. Since the lifetimes of these daughters are all less than 30 minutes, the level of radon should be affected by the infiltration rate of clean air. Because of this, the EPA has recommended guidelines to the state of Florida to consider remedial action to lower the radon level below about 2 to 3 pCi/l.

The air filters into a building because of temperature differences and because of the Bernoulli effect caused by wind velocity. Because the infiltration of outside air replaces the air in the buildings causes a loss of about 25% of the energy to heat and cool our buildings, many "house doctor" groups are considering ways to reduce this needless loss of energy. Because of the infiltration pathways, the typical house has about one air change per hour (ach). There is a much wider variation (about 2 to 3 orders of magnitude) in the source term (the rate of radon infiltration) in the nation's housing stock than there is in the rate of exchanges of outside air (about 1 order of magnitude in ach). The source term varies so much that one should consider the health effects of very tight housing on a case-by-case basis by measuring the indoor air quality. If the leakage pathways were reduced to 0.33 ach on new construction, the energy loss by infiltration would be reduced to 33% of its former value. On existing buildings "house doctors" can use blower doors to find the leakage pathways and reduce infiltration to about 0.5 ach. Of course, the "house doctors" should save the energy, but what will be the health effects of the increased radon levels and increased indoor air pollution in our buildings? Can we have both conservation and clean air?

III.A ENERGY SAVINGS FROM REDUCED INFILTRATION. Let us estimate how much energy could be saved if the rate of air exchange was reduced from 1 ach to 0.5 ach? Assume the following: (1) The 70 million American living units have an average of 130 m^2 (1500 ft^2) floor space and 2.5 m (8.5 ft) ceilings; (2) The mass density of air is 1.2 kg/m^3 (0.0735 lb/ft^3) and its specific heat is $C = 1.0 \text{ J/g}^\circ\text{C}$ ($0.238 \text{ BTU/lb}^\circ\text{F}$); (3) The average heating season for the U.S. is about 2670°C (4800°F) degree days/year (dd/y); and (4) The average efficiency of a furnace is $\eta = 2/3$.

The rate of energy lost by infiltration is

$$dQ/dt = (dm/dt)(C)(\Delta T)/(\eta)$$

where dm/dt is the infiltration rate of air mass, and ΔT is the temperature difference between the outside and the inside, 18.3°C (65°F) - $T(\text{outside})$. Integrating this loss rate over the year, we obtain the energy lost by infiltration from a building over a year

$$Q = (dm/dt)(C)(dd/y)(24 \text{ h/d})/()$$

where dd/y is the number of degree days per year, $(1/24) \int (T) dt$ where t is in hours. It follows that the energy saved by closing the nation's infiltration pathways could be as high as

$$\begin{aligned} & (1 \text{ ach} - 0.5 \text{ ach})(130 \times 2.5 \text{ m}^3)(1.2 \text{ kg/m}^3)(24 \text{ h/d}) \\ & (1000 \text{ J/kg}^\circ\text{C})(2670 \text{ dd/y})(7 \times 10^7 \text{ homes})(3/2) \\ & = 1.3 \times 10^{18} \text{ J/y} = 1.2 \times 10^{15} \text{ BTU/y} = 1.2 \text{ quads/y.} \end{aligned}$$

This value is equivalent to 0.6 Mb/d of oil (13% of the 4 to 5 Mb/d that is used to heat the nation's homes), or 1.2 trillion cubic feet of natural gas (6% of the annual consumption of natural gas). Additional energy savings would come from reduced air conditioning as well as from commercial and industrial buildings.

III.B RADON FROM REDUCED INFILTRATION. Let us estimate very approximately the increase in the U.S. cancer rate if the infiltration rate of all houses was reduced from 1 ach to 0.5 ach. We will assume that the hypothesis that accepts a linear relationship between low-dose radiation and increased probability of getting lung cancer is correct; a doubling of the low-dose radiation level will double the probability of getting cancer from that particular source of radiation. For the purposes of this calculation we will use analysis of the excess cancer rate of uranium miners that was carried out by the United Nations Committee on Radiation (UNSCEAR). From their review of the relevant data on uranium miners (which appear to be approximately linear) they concluded that about 100 annual additional cases of lung cancer would be caused if one million persons spent all of their time in an environment with 1 pCi/l of radon-222. Some observers consider that the UNSCEAR number to be a factor of two too large, and that the other uncertainties of the radon problem cause a total uncertainty of about a factor of 10. We will assume that persons will spend about 50% of their time inside their homes.

If the air change rate is reduced by a factor of two from 1 ach to 0.5 ach, the radon level in the buildings would be increased by a factor of two from about 1 to 2 pCi/l. The number of additional cases of lung cancer could be

$$(2 - 1)(\text{pCi/l})(10^{-4}/\text{pCi-y/l})(2.3 \times 10^8/\text{US})/2 = 10,000/\text{y}$$

within a range of 2,000 to 20,000/y. Since this result is about 10% of the present number of new lung cancer victims per year in the U.S. (100,000/y), indoor radon appears to be a significant contribution. In fact, the U.S. Environmental Protection Agency, Canada, and the Scandinavian countries have recommended guidelines to minimize the radon problem; for example the Sweden has recommended a minimum ventilation rate standard of 0.5 ach and 2 pCi/l for newly constructed homes.

Fortuitously, there is a technical fix so that we can have both conservation and health; Japan and the European nations are already marketing a \$400 air-to-air heat exchanger that transfers about 75% of the heat energy from the exhaust air to the clean incoming air. The payback period will depend on a variety of factors such as climate, new/old construction, desired number of ACH, costs, etc. These heat exchangers would also allow the possibility of reducing the present radon concentration in our current untightened buildings which cause about 10,000 lung cancers per year. It is clear that there is a point of diminishing return in tightening a house too much when considering a house with an air-to-air heat exchanger. Since the energy loss rate is proportional to the number of ACH, and the harmful health effects are inversely proportional to the number of ACH, there is an optimal spread of ACH values, depending on the quality of the indoor air in a particular house.

IV: ACID RAIN

The increased burning of coal contains sulfur has exacerbated the problem of acid rain⁹ in the United States and in Europe. The most extreme example of acid rain with a pH of 2.4 (equivalent to vinegar) was recorded in Scotland in 1974. The average pH of the rainfall in some regions of the eastern U.S. has fallen to about 4.1. The pH of the rain in Pasadena, California has ranged between 2.7 and 5.4 with an average of 3.9. (Because of the CO₂ in the atmosphere, the pH of normal rain is about 5.6.) Even the rain in the Rocky Mountains has become considerably more acidic (from increased NO_x emissions); the pH of the rain in Colorado dropped from 5.4 to 4.6 in the three year time span of 1975 to 1978. Since water with an excess acidity (pH below 4 or 5) interferes with reproduction and spawning of fish, it has become difficult to support fish life in some lakes.

IV.A EASTERN AND WESTERN COAL. In 1979 the EPA relaxed the SO₂ emissions standards so that western coal (subbituminous) would not have to be scrubbed to the former standard of 90% sulfur removal on new electrical power plants; in the future, plants burning western coal would only have to have 70% of its SO₂ removed. This new formulation of the standard would result in approximately the same rate of sulfur emissions on an energy basis (lbs/BTU) from both kinds of coal. Eastern coal (bituminous) contains about 2.5% sulfur and has about 12,500 BTU/lb while Western coal has about 8,500 BTU/lb. Since the rate of sulfur emissions from eastern (2.5%) and western coal will be approximately the same, we can determine the sulfur content of western coal (W%)

$$(2.5\%)(100\% - 90\%)/(12,500 \text{ BTU/lb}) = (W\%)(100\% - 70\%)/(8500 \frac{\text{BTU}}{\text{lb}})$$

From this we obtain $W = 0.57\%$ which is quite close to the sulfur content of 0.5% for western coal. The Western coal has less sulfur

because it was formed under fresh water while the eastern coal was formed under salt water.

IV.B. ACID RAIN. Let us calculate very approximately the average pH of rain in the U.S. We assume the following: (1) Most of the sulfur comes from the burning of about 600 million tons/year of coal which has an average sulfur content of about 2% (by weight); (2) the U.S. has an area of about 3 million square miles ($7.7 \times 10^6 \text{ km}^2$) with an average rainfall of about 25 inches (0.63 m); and (3) The nitrogen oxide compounds contribute about one-third of the total acidity. (In the western U.S. NO_x can be the predominant cause of the acidity.)

$$\begin{aligned} &\text{The number of gram moles of } \text{H}_2\text{SO}_4 \text{ produced each year is about} \\ &(0.02)(600 \times 10^6 \text{ tons})(9.1 \times 10^5 \text{ g/ton})/(32 \text{ MolWt of S}) \\ &= 3.4 \times 10^{11} \text{ gram-moles/y.} \end{aligned}$$

The number of gram moles of hydrogen ions will be three times this figure because H_2SO_4 contributes two ions and the NO_x compounds one third of the total acidity. The volume of rain that falls on the U.S. each year is about

$$(7.7 \times 10^{12} \text{ m}^2)(0.63 \text{ m})(10^3 \text{ l/m}^3) = 4.8 \times 10^{15} \text{ liters/y.}$$

The maximum possible average pH of the rain in the U.S is obtained by taking the logarithm of the ratio of

$$(1.0 \times 10^{12} \text{ moles})/(4.8 \times 10^{15} \text{ liters}) = 2.1 \times 10^{-4}$$

which gives a pH of about 3.7. This value is considerably lower than the average value of about 4.5 for the eastern U.S. for at least two reasons, tall smoke stacks and "dry" acid rain. The tall 300 meter smoke stacks tend to disperse the acid rain to other places such as Canada, the Atlantic Ocean, and Europe. In addition, the acidity of the acid rain will be further reduced since about 20% of the sulfur is deposited onto the earth as a "dry" acid rain made up of small particulates.

IV.C POWER PLANT PLUMES. The calculation of the dispersal of SO_2 from a power plant is difficult because turbulence and thermal eddies in the air are considerably more important than classical molecular diffusion. In addition the local geography can severely modify the air currents so that any simple formulation of the problem can be incorrect by an order of magnitude. However, an approximate¹⁰ solution to this difficult problem is meaningful since it forces us to focus on the basic science of SO_2 plumes from a power plant. Let us assume that the steady state diffusion equation is valid for the large distances in the direction of the wind, x , such that $x^2 \gg (y^2 + z^2)$;

$$U \frac{\partial C}{\partial x} = D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2}$$

where U is the wind velocity in the x direction, C is the concentration of the impurity (SO_2 in this case), and D_y and D_z are the macro diffusion constants which are about 6 orders of magnitude larger than the molecular diffusion constants in completely still air. It can be easily shown that the solution to this equation is

$$C = \frac{S}{2\pi U \sigma_y \sigma_z} \exp(-(y^2/\sigma_y^2 + z^2/\sigma_z^2)/2)$$

where S is the emission rate of SO_2 and the standard deviation widths of the Gaussian solutions are given by $\sigma_y = \sqrt{2D_y/U}$. Let us determine the SO_2 concentrations in the direction of the wind ($y = 0$) at distances of $x = 1$ km and 10 km from the power plant. We will also determine the SO_2 concentrations at the center of the plume that has risen from a tall smokestack (300 m above the ground) and at ground level. Assume the following: (1) A 1 GWe power plant burns about 10^4 tons of coal per day with a 2% sulfur content; (2) the wind velocity is 5 m/s; (3) the diffusion constants (enhanced by turbulence) are $D_y = D_z = 25 \text{ m}^2/\text{s}$ (for slightly unstable (Pasquill-Gifford) stability condition); (4) the SO reflected from the earth can be treated as an image source 300 m below the earth; and (5) a concentration of 2.6 mg/m^3 of SO_2 corresponds to 1 ppm. Compare your answer to the threshold for increased hospital admissions when SO_2 concentrations exceed 0.1 ppm for 4 days or when SO_2 exceeds 1.0 ppm for 5 minutes. These pollution levels can be compared to the extreme case of London in 1952 when 3 days of 0.7 ppm of SO_2 (and particulates) caused about 2500 excess deaths.

The standard deviations for the SO_2 distribution is

$$\sigma = \sqrt{(2)(25)(1000)/(5)} = 100 \text{ m}$$

at a distance of 1 km and $\sigma = 316 \text{ m}$ at 10 km. The power plant emits sulfur at the rate of

$$S = (0.02 \times 10^4 \text{ tons/d})(910 \text{ kg/ton})/(8.6 \times 10^4 \text{ s/d}) = 2.1 \text{ kg/s.}$$

Since the molecular weight of SO_2 is twice that of sulfur, this corresponds to 4.2 kg/s of SO_2 . Inserting these values into the solutions of the diffusion equation for the sources at $z = 300 \text{ m}$ and $z = -300 \text{ m}$, we obtain $C(x, y, z)$ for the following places (in km): $C(1, 0, 0.3) = 5.1 \text{ ppm}$, $C(1, 0, 0) = 0.11 \text{ ppm}$, $C(10, 0, 0.3) = 0.60 \text{ ppm}$, $C(10, 0, 0) = 0.66 \text{ ppm}$. From these values we see that the SO_2 concentration has decreased by almost a factor of ten within the plume ($y = 0$, $z = 0.3$) as the distance from the plant was increased from 1 to 10 km. However, we note that the SO_2 concentration at ground level ($z = 0$) has increased over this distance from 0.11 ppm to 0.60 ppm. The tall smokestack has decreased the severity of the problem, but it has shifted the highest dose rates to more distant neighbors. Since these values of SO_2 exceed the conditions for increased hospital admittance, it is clear that one should not remain

in the plume.

IV.D POLLUTION SCALING LAW. City A has a size of L km by L km and it has a SO_2 level of 0.015 ppm. The SO_2 is emitted at a constant rate per unit area from many small sources. Let us determine the SO_2 level in city B that has exactly the same weather conditions, and pollution production density, but B has an area of $10L$ by $10L$?

Since B is 100 times larger it will produce 100 times as much pollution. Since the wind will blow the pollution away through a cross-sectional area of LH (where H is the inversion layer) that is only 10 times larger for city B, the pollution level in city B will be 10 times larger than city A. The SO_2 level of 0.15 ppm in city B exceeds the Primary (Public Health) Air Quality Standard of 0.14 ppm for a maximum 24 hour concentration.

V: LNG EXPLOSIONS

The amount of liquified natural gas (LNG) that will be transported in the future may increase because some regions of the world need natural gas and other regions of the world are faced with the choice of either flaring the gas in the atmosphere or selling it. Most of the LNG will be transported in ships which contain up to five spherical tanks with a diameter of 35 m that will hold about $25,000 \text{ m}^3$ of LNG. If one of the spherical tanks should rupture, the LNG vapors would spread horizontally, rather than rise, because the density of the cold vapors (-160°C) is greater than the density of air. Let us estimate the equivalent explosive energy and power if one of the spherical tanks should rupture and explode.¹¹ Assume the following: (1) The energy content of LNG is about $3.3 \times 10^{10} \text{ J/m}^3$; (2) One kiloton of explosives has an energy equivalence of 10^{12} calories; and (3) The type of LNG explosion will depend on atmospheric conditions and on the time of ignition as to whether it would be a horizontal fire storm or a "fireball", but for this example we will assume it takes five minutes to the burn all the LNG.

The explosive energy available from one of the spherical tanks is

$$E = (2.5 \times 10^4 \text{ m}^3)(3.3 \times 10^{10} \text{ J/m}^3) = 8.2 \times 10^{14} \text{ J} = 200 \text{ kilotons}$$

which is about 15 times that of the Hiroshima bomb. The average explosive power during the 5 minute burn is

$$P = E/t = (8.2 \times 10^{14} \text{ J})/(300 \text{ s}) = 2.7 \times 10^{12} \text{ W} = 2700 \text{ GWt}$$

which is about the same as the thermal power of the U.S. ($2500 \text{ GWt} = 78 \times 10^{15} \text{ BTU/y}$). If the duration of the fireball was 30 seconds, the explosive power would have been 10 times higher. If all five

spherical containers in a large LNG tanker exploded, the energy and power values would be five times higher.

REFERENCES

1. A good general reference on the methodology of environmental risk is by W. Lowrance, *OF ACCEPTABLE RISK*, Kaufmann, Los Altos, California, 1976. More specific estimates on risks from energy production can be found in: J. Holdren, G. Morris, and I. Mintzer, *Ann. Rev. Energy* 5, 241 (1980). B. Cohen and I. Lee, *Health Physics* 36, 707 (1979). R. Wilson and E. Crouch, *RISK BENEFIT ANALYSIS*, Ballinger, Cambridge, MA, 1983. D. Hafemeister, *Am. J. Phys.* 50, 713 (1982).
2. S. Schneider and R. Chen, *Ann. Rev. Energy* 5, 107 (1980). J. Williams, *CARBON DIOXIDE AND SOCIETY*, Pergamon Press, Oxford, 1978. *CHANGING CLIMATE*, National Academy of Sciences, Washington, DC, 1983.
3. C.D. Keeling, R.B. Bacastow, and T.P. Whorf, "Measurements of Concentration of Carbon Dioxide at Mauna Loa Observatory, Hawaii," in *CARBON DIOXIDE REVIEW: 1982*, W.C. Clark, editor, Oxford Univ. Press, p. 377-385 (1982), and unpublished data courtesy of C.D. Keeling. The measurements were obtained in a cooperative program of the U.S. National Oceanic and Atmospheric Administration, and the Scripps Institution of Oceanography.
4. J. Laurmann, *Science* 205, 896 (1979).
5. A. Nero, *A GUIDEBOOK TO NUCLEAR REACTORS*, Univ. California Press, Berkeley, 1979.
6. Reports to the American Physical Society: *REACTOR SAFETY STUDY*, *Rev. Mod. Phys.* 47, S1, S95 (1975), and *RADIONUCLIDE RELEASE FROM SEVERE ACCIDENTS AT NUCLEAR POWER PLANTS*, *Rev. Mod. Physics* 57 (1985).
7. H. Agnew, *Sci. Amer.* 244, 55 (June, 1981).
8. R. Budnitz, J. Berk, C. Hollowell, W. Nazaroff, A. Nero, and A. Rosenfeld, *Energy and Buildings* 2, 209 (1979). J. Spengler and K. Sexton, *Science* 221, 9 (1983). Entire issue of *Health Physics* 42, January, 1983. Chapter by R. Sextro, et al in this book.
9. G. Likens, R. Wright, J. Galloway and T. Butler, *Sci. Amer.* 241, 43 (Oct. 1979). *ACID RAIN AND TRANSPORTED AIR POLLUTANTS*, Off. Technology Assessment, Washington, DC, 1984. *ACID DEPOSITION: ATMOSPHERIC PROCESSES IN EASTERN NORTH AMERICA*, National Academy of Sciences, Washington, DC, 1983. K. Rahn and D. Lowenthal, *Science* 228 (1985).
10. S. Williamson, *FUNDAMENTALS OF AIR POLLUTION*, Addison-Wesley, Reading, Mass., 1973. J. Seinfeld, *AIR POLLUTION*, McGraw Hill, New York, 1975.
11. *TRANSPORTATION OF LIQUIFIED NATURAL GAS*, Office of Technology Assessment, U.S. Congress, Washington, 1977. J. Fay, *Ann. Rev. Energy* 5, 89 (1980).