LONG TERM CONSEQUENCES OF THE LINEAR-NO THRESHOLD DOSE-RESPONSE RELATIONSHIP FOR CHEMICAL CARCINOGENS

Bernard L. Cohen
University of Pittsburgh
Pittsburgh, PA 15260

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A consortium of government agencies led by the Environmental Protection Agency has adopted a linear, no threshold dose-response relationship for chemical carcinogens. It is the purpose of this paper to point out some very important consequences of this action for long term risk assessments of various technologies. These consequences arise from the fact that the bulk of the waste products from most technologies end up in the ground, and the probability for eventual transfer from the ground into oral ingestion by humans is relatively large when integrated over very long time periods. These considerations apply most clearly to the carcinogenic elements, the widely accepted list of which now includes beryllium, chromium, nickel, arsenic, and cadmium. We begin by discussing the carcinogenicity of these elements for human ingestion, then consider their transfer probability from soil into human oral ingestion, and finally give applications of these results to risk analyses for a few technologies.

CANCER RISK FROM CARCINOGENIC ELEMENTS

The consortium of Federal agencies recognizes the EPA Carcinogen Assessment Group (CAG) as the primary source of evaluations of carcinogenicities. With the linear, no threshold dose-response relationship, this simply involves determining a simple number for each substance, the slope of the line depicting this relationship, or the risk per gram of intake. Note that this number does not depend on the rate or quantity of intake. (It does, of course, depend on whether intake is by inhalation or oral ingestion.)

A basic source of information on carcinogenicities is the CAG documents, and the other official U.S. source is

the Water Quality Criteria Documents (WQCD). Unfortunately, CAG does not do assessments on a routine and systematic basis but rather provides an assessment only when requested to do so by some government agency. In some cases it is therefore necessary to extend their coverage. The resulting risks are listed in Columns (2) and (3) of Table I. The "primary" risks are those from CAG, and the secondary are derived from other sources as back-ups if the primary estimates are not accepted. In the remainder of this paper, we use the primary risks except for nickel for which CAG has not done an assessment.

There may be some tendency to discount the risks listed in Table I as based on relatively meager data. To some extent this is a reasonable criticism, especially in a few specific cases. However, there are also good reasons to believe that they may underestimate the true effects. In four of the five elements, lung cancer carcinogenicity is rather well established; for example, they are officially listed as established carcinogens in Sweden, Germany, and USSR. But this is just what one would expect from sparsity of data. Most data are from industrial exposures in which nearly all intake is by inhalation, so lung cancer would be the most easily discovered. There is no a priori reason to believe that the lung is much more susceptible to cancer than other body organs. For example, in whole body exposure to radiation it accounts for only about 25% of all cancers. It therefore seems highly probable that if there were extensive experience with oral ingestion we would find much more and better evidence for cancers in various other organs initiated by these elements. In this sense, then, Table I underestimates the seriousness of the situation; if some of the risks listed there are over-stated, there are probably other comparable or larger risks that are omitted. In addition there is evidence for carcinogenicity in other elements, including iron and perhaps Pb, and there are many elements for which no studies are available.

TRANSFER FROM THE GROUND TO HUMAN ORAL INGESTION

In nearly all situations, metals used by industry or in other human endeavors end up in the ground. In order to assess the health effects, we must therefore estimate the probability for an atom in the ground to eventually enter a human body by oral ingestion. From chemical analyses of food and water supplies, there is now a great deal of information on the average quantities of each element orally ingested each year by humans. These data are collected and evaluated in ICRP Publication No. 23. The total quantity orally ingested per year in the United States is obtained by multiplying them by the U.S. population and the number of days per year; for example, the total quantity of arsenic ingested orally by humans in the U.S. is 8.4×10^7 gm/yr.

Table I: Risks from oral ingestion of carcinogenic elements and their transfer probability from the ground to human oral ingestion. 5.3E-3 means 5.3×10^{-3}

(1)	(2)	(3)	(4)	(5)
element	risk/gm ingested primary	back-up	transfer prob.	fatalities/ te in grd.
Be	5.3E-3	1.8E-5	5.4E-4	2.9
Cr	~1.0E-3	1.3E-5	1.9E-4	.19
Ni	-	8E-5	5.9E-4	.047
As	1.0E-4	4E-5	4.7E-2	4.7
Cd	1.3E-3	-	6.5E-2	42*

*Cd causes cancer which is a male disease, so females are unaffected halving the number of fatalities.

The principal alternative fate of material in the ground is to be washed into the oceans by rivers. North American rivers carry into the oceans 120 gm/yr of dissolved and suspended material for each square meter of continental surface area, so the material removed from the $8 \times 10^{12} m^2$ area of the U.S. (48 contiguous states) is ($120 \times 8 \times 10^{12} =$) 10^{15} gm/yr. The quantity of each element removed is obtained by multiplying this number by the concentration of that element in the ground; for example, for As the removal rate is 1.8×10^9 gm/yr.

The probability for an atom of As in the ground to be orally ingested by a human before it is washed into the ocean is then ($8.4 \times 10^7 / 1.8 \times 10^9 =$) 4.7%. This is listed in Col. (4) of Table I, along with values for the other elements.

Some materials are released as airborne dust, but they eventually settle down to the ground and become part of the soil. Some materials are released by industry into rivers and never get into the ground, but this also has pathways into oral human ingestion through water supplies and irrigation of food crops. If we consider only the former, we can estimate the transfer probability to be 1.0×10^{-4}. If this probability also applies to material dumped into rivers, we see that it is less than the eventual oral ingestion probability of material in soil as listed in Col. (4) of Table I. This leads to the surprising conclusion that from the long range viewpoint, it is safer to dump the materials listed in Table I into rivers than to bury them in the ground! In addition it should be recognized that when the material is eventually released from soil it will very probably eventually get into rivers and hence the danger of dumping it directly into rivers is not avoided; whereas the danger from land burial due to pick-up by plant roots leading to food pathways is avoided by direct dumping into rivers (if they are not used for irrigation). The safest procedure from this perspective is to dump the materials directly into the ocean where they will eventually end up in any case.

It should be noted that current regulatory pressures are to use land burial in preference to river or ocean dumping, even though this frequently adds substantially to costs. This can perhaps be justified by the fact that health effects are delayed to later generations rather than being experienced in the near future, but if that viewpoint is accepted, consistency requires other alterations in attitudes including a drastic downward revision of fears from radioactive waste.

Since the great majority of disposal of metals like those listed in Table I is into the ground, we will use the transfer probabilities in Col. (4) of Table I in the remainder of this paper. The fatalities expected per tonne can then be calculated by multiplying the risk from Col. (2) by the transfer probability from Col. (6) and using the conversion

from gm to te. For example, for As, this is 1.0×10^{-4}/gm ingested $\times 10^{6} \frac{gm}{te} \times 4.7 \times 10^{-2} \frac{te\ ingested}{te\ in\ ground} = 4.7$ fatalities/ tonne in the ground. This is listed in Col. (5), and we see from the example that it is Col. (2) x Col. (4) x 10^{6}; values obtained in this way are listed for all cases in Col. (5). Note that Cd causes prostate cancer which affects males only, so the number of expected fatalities is reduced in half.

It will be useful in later discussions to know the time scale for this transfer, so we now turn to that problem.

If we take the density of the ground to be 2.5×10^{6} gm/m^3, the 120 gm/yr-m^2 of average erosion in the U.S. corresponds to $(120/2.5 \times 10^{6} =) 5 \times 10^{-5}$m per year, or the removal of 1 meter every 20,000 years. The great majority of this erosion is from stream beds, but streams change their courses frequently, and geological and climatological patterns change to create new rivers and drainage systems; if this were not so, the roughly 0.1% of U.S. land surface covered by streams would be converted to canyons averaging 1000 meters deep after 20,000 years, and continue to deepen linearly with time thereafter. When averaging effects over a hundred thousand years or so, it is clearly much closer to reality to consider a reasonable fraction of all land to be eroding at the 1m/20,000 yr average rate. Of course some of the present U.S. surface will not erode and will even be further covered by sediment in this time period, but this probably represents a small minority of the entire surface. Any elaborate treatment of this subject would have to be very lengthy and somewhat controversial, so it is best left to geologists. For purposes of loose discussion we will take the time constant for transfer into the oceans of material within a few meters of the earth's surface to be of the order of 100,000 years, although it should be recognized that a considerable fraction is transferred in a much shorter time, and a significant fraction will not be transferred for many millions of years. Since the transfer from the ground to oral human ingestion must take place before the transfer to the oceans, we will take the time constant for the former process to be of the order of 100,000 years.

HEALTH EFFECTS OF COAL-FIRED ELECTRICITY PRODUCTION

As our first application of the above discussions, we consider electricity generation by coal burning. Coal contains trace amounts of the elements listed in Table I, and when the coal is burned and the ash is buried or handled in most other ways these metals generally end up in the ground, where they cause fatalities at rates listed in Col. (5) of Table I and reproduced in Col. (2) of Table II.

Table II: Calculation of health impacts of coal burning and of commercial use of carcinogenic elements

(1) element	(2) deaths/te in grd	(3) ppm in coal	(4) deaths/GWe-yr 10^5yr	(5) deaths/GWe-yr 10^7yr	(6) tonne/yr in US domestic	(7) tonne/yr in US imported	(8) fatalities/yr domestic	(9) fatalities/yr imported
Be	2.9	1.5	13	16	200	110	580	320
Cr	.19	12	7	39	60,000	400,000	11,000	76,000
Ni	.047	10	1.4	8	12,000	200,000	560	9,400
As	4.7	14	200	25	2,000	11,000	9,400	52,000
Cd	42	0.8	100	24	1,800	3,700	76,000	156,000
		TOTALS	320	112			98,000	294,000

Generation of 1GWe-yr of electrical energy requires burning about 3×10^6 metric tonne (te) of coal. The average concentrations of carcinogenic metals in U.S. coal are listed in Col. (3) of Table II, and the quantity ending up in the ground is obtained by multiplying it by 3×10^6te/GWe-yr. The number of resulting fatalities is then found by multiplying this by Col. (2). For example, coal contains 14 ppm of As, so 1 GWe-yr of coal burning releases ($3 \times 10^6 \times 14 \times 10^{-6}$ =) 42 te of As into the ground, and this will eventually cause (42 x 4.7 =) 200 fatalities. This is listed in Col. (4) of Table II, as are the fatalities/GWe-yr obtained analogously for the other carcinogenic elements.

The total effect of the elements listed is about 320 fatalities/GWe-yr from coal burning electricity, most of them occurring within $\sim 10^5$ years. This is an order of magnitude higher than typical estimates of fatalities from air pollution, and three orders of magnitude higher than those from the radioactive waste of nuclear energy.

One could point out that these carcinogenic trace metals in coal would have eventually reached the surface by erosion even if the coal had not been mined, so these fatalities should not be classified as additional. The only effect of coal burning would then be to cause these fatalities to occur within 10^5 years rather than in about 10^7 years as would be expected from the average erosion rate and the depth of coal deposits. However, this argument is not quite valid, for the following rather subtle reason.

It is true that the trace elements in the coal would make the same eventual contribution to health effects whether or not the coal was mined. But the same is not true of the carbon in the coal. If this carbon were left in the ground, it would have no effect as a carcinogenic element when erosion brought it to the surface. However, if it is mined and burned, its turn near the surface is taken by "average rock", and the latter does contain trace amounts of carcinogenic elements. It is these that contribute extra eventual fatalities.

If we ignore differences in density, the 3×10^6 tonne/GWe-yr of carbon is replaced by 3×10^6 tonne/GWe-yr of average rock. This contains 5.4 tonne of As which, according to Col. (2) of Table II will cause (5.4 x 4.7 =) 25 fatalities. This is listed in Col. (5) of Table II as are values for the other elements obtained analogously. For arsenic, the fact that there are 200 fatalities/GWe-yr in 10^5yr but only 25 fatalities/GWe-yr in 10^7yr implies that 175 lives are saved in the latter period. This is clear from the fact that coal contains much more arsenic than the average rock that replaces it, so if the coal were mined and disposed of without releasing its contained arsenic, arsenic exposure to humans would be reduced. The long term eventual toll adds up to

112 fatalities/GWe-yr which is still much larger than the effects of air pollution or any other environmental pollutant considered in the past.

One could argue that the average rock that replaces the coal would eventually have reached the surface even if the coal had not been mined. In fact, one might think that all the carcinogenic elements in the earth's crust will eventually have their turn near the surface whether or not coal is mined. However this argument ignores the erosion-subduction-uplift cycle which continually recycles material through the crust such that there will always be the same quantity of carcinogenic elements in average rock.

The total coal mined annually in the U.S. is about 700 x 10^6te, enough to produce 230 GWe-yr of electricity. The fatality toll due to this is then (230 x 320 =) 74,000 per year of coal use, spread over the next 10^5 years, and (230 x 112 =) 26,000 per year of coal use averaged over the next 10^7 years.

FATALITIES FROM COMMERCIAL USE OF CARCINOGENIC ELEMENTS

The carcinogenic elements are used commercially for a variety of applications, and in essentially all of them, the material ends up in the ground where it can be expected to cause eventual cancers. The annual primary domestic production and imports for the U.S. in the early 1970s are listed in Col. (6) and (7) of Table II, and their health consequences are obtained by multiplying these by Col. (2), giving the results listed in Col. (8) and (9) of Table II. These fatalities would be mostly spread over a time period of 10^5 years. In the case of domestic production, these are fatalities that would be expected to occur in the absence of mining when erosion would have brought the material to the surface, so on a 10^7 year time scale there are no net fatalities. But for imported material, these are additional fatalities in the U.S. population, with no later compensating effects. We have not considered secondary production such as extraction of arsenic from copper ores, since fatalities from these should probably be charged to the primary product. In that example, about 7300 te/yr of As is extracted from imported copper, so the 35,000 fatalities it is expected to cause in the U.S. should be charged to these copper imports.

We see from Col. (8) and (9) of Table II that each year's use of these materials can eventually be expected to cause hundreds of thousands of fatal cancers. Since their use at present rates can be expected to continue for an average of perhaps 50 years, these problems involve tens of millions of eventual fatalities.

PHOTOVOLTAIC ELECTRICITY

Since solar energy is widely believed to be environmentally benign, it is interesting to consider the impact of the problems under consideration on that technology. One photovoltaic cell material under consideration is CdS. It is estimated that this will require 54 tonne of Cd/GWe-yr. Our estimate of 42 fatalities/te of Cd in the ground would then predict 2200 fatalities/GWe-yr, making this by far the most dangerous of all technologies for electricity production.

Another candidate for photovoltaic cells is GaAs, which requires 14 tonne of As/GWe-yr. Our estimate of 4.7 fatalities/GWe-yr then predicts 66 fatalities/GWe-yr.

All solar photovoltaic technologies require large quantities of steel, cement, glass, and probably aluminum, for deployment of the large arrays of solar cells, and these, in turn require burning a great deal of coal which has the health problems discussed previously. A recent design study of low cost structures for photovoltaic arrays was used to calculate that these use 12.5 lb-coal/ft^2 of collector.

A photovoltaic collector may be expected to produce a peak of about 10 watts/ft^2 which corresponds to a time average over the day and night and the seasons of the year of perhaps 2 watts/ft^2. A 1 GWe-average array would then have an area of 5×10^8 ft^2, which requires the burning of ($12.5 \times 5 \times 10^8$ =) 6×10^9lb of coal. If the array operates for 30 years, it will produce 30 GWe-yr, so its coal use is 2×10^8lb/GWe-yr $\approx 10^5$ tonne coal/GWe-yr. Since direct production of electricity by coal burning power plants uses 3×10^6 tonne/GWe-yr and causes 320 fatalities/GWe-yr, (Col. (4) of Table II), we conclude that photovoltaic arrays will cause ($320 \times 10^5/3 \times 10^6$ =) 10 fatalities/GWe-yr through release of carcinogenic elements. This is quite comparable to effects usually ascribed to the dirtier energy technologies.

THE LINEAR-NO THRESHOLD DOSE-RESPONSE RELATIONSHIP

The health effects calculated in this paper are very much more serious than those that have been estimated in the past from any peaceful technology. The reason for this is the linear, no threshold dose-response relationship which has been adopted for chemical carcinogens.

The situation for chemical carcinogens is now similar to that for radiation, and in fact the techniques used in this paper were developed originally for evaluations of radioactive waste. However, the dangers from chemical carcinogens are much more serious than from radioactive waste because the latter decays away with time whereas the

former persist forever. Moreover, the radioactive waste is small in quantity so it is easily converted to favorable chemical forms and buried deep underground, whereas the carcinogenic elements are so large in quantity and so highly dispersed and diluted that such action would be completely impractical.

The justification for the linear-no threshold dose-response relationship leaves much to be desired, and there is certainly no experimental evidence supporting it at low doses. However, again the situation is analogous for radiaction, and the absence of contrary evidence seems to sustain its use in spite of the absence of support for, and occasional admonitions against that practice by prestigeous scientific committees.