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SOME LONG-RANGE SPECULATIONS ABOUT COAL

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ABSTRACT

Should the world demand for energy increase sixfold within the next 50 years, largely because the underdeveloped countries industrialize, and if half this demand is met by coal, then the estimated world recoverable resource of coal of 4×10^{12} metric tons would last at this asymptotic level about 140 years. The carbon dioxide concentration in the atmosphere is then estimated to increase about threefold. These two eventualities may place limits on our ultimate use of coal. The risk of a CO_2 accumulation inherent in the widespread use of coal is in a sense analogous to the risk of nuclear proliferation: both problems are global, uncertain, and could pose profound challenges to man's future.

SOME LONG-RANGE SPECULATIONS ABOUT COAL*

We shall speculate on the role of coal in the intermediate future, say to 2010; and in the very distant future, beyond 2010 when replacements for fossil fuels may have to be used on a large scale.

— Do We Have Enough Coal? —

When will our coal reserve be seriously depleted? In Table 1 we summarize our coal reserve based on estimates given by P. Averitt in 1975.[1]

TABLE 1. U.S. AND WORLD COAL RESOURCES

	U.S.		World	
	Billion Metric Tons	10^{15} Kilojoules	Billion Metric Tons	10^{15} Kilojoules
Resources	3,600	86,300	15,074	360,000
Ultimately available resource	941	22,600	3,940	95,000
Reserve base	394	10,300	1,650	43,000
Reserves	197	5,150	824	21,500

Note that the U.S. reserves of coal, defined as 50 percent of the coal that has been accurately identified and is currently economic to recover, amounts to but 5 percent of the total U.S. resource — the latter being defined as all coal in seams no thinner than 14 inches (35 cm) nor deeper

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than 6,000 feet (1,800 m). We are thus confronted with an immense range of possibilities between what is now judged to be economically recoverable and what the total resource is. Since coal in seams as thin as 14 inches (35 cm) is mined in some places, and in mines as deep as 3,500 feet (1,100 m) in others, one simply cannot assert that we shall never exploit a great part of the resource. The second entry for the United States, designated "ultimately available resource", represents Averitt's estimate of how much coal there is at 3,000 feet (900 m) depth or less in seams 28 inches (70 cm) thick or thicker; and he regards 50 percent of this as "ultimately available". For the world we show the same fraction of "resources" as Averitt estimated for the United States.

Let us now examine possible bounds on the amount of coal that is actually used. These bounds may arise from limitation of overall energy demand, from environmental effects, or from competition from alternative sources of energy.

Most recent estimates of the future demand for energy have been lower than they were say, a half-dozen years ago. Much of our basic energy policy in the United States was formulated when we took as a law of nature, more or less, that energy demand would increase at the historic rate of 4.5 percent per year ad infinitum. But beginning with the Ford energy project,[2] and now with increasing frequency, we are getting accustomed to much lower projections of energy growth. Thus the ORAU Institute for Energy Analysis, in its study[3] "Economic and Environmental Implications of a U.S. Nuclear Moratorium, 1985-2010" (abbreviated USNM),

projects a high aggregate U.S. energy demand in 2000 of 126 quads (133×10^{15} kilojoules), a low of 101 quads (106×10^{15} kilojoules). The low figure agrees with the Ford zero energy growth estimate.

At the time Ford zero energy growth was promulgated, much of the establishment reacted violently — yet only 3 years later such low projections receive nods of approval, and seem to be incorporated into our national energy policy. Three major factors give to such lower estimates a feel of plausibility: (1) a lower fertility rate (1.8 per woman) and therefore a population around 250×10^6 instead of 350×10^6 by the turn of the century; (2) a trend toward conservation induced both by government fiat and by rising energy prices; and (3) a lower rate of increase of labor productivity and therefore of gross national product (GNP). Though there is no constant relation between GNP and energy, the slower rise in GNP would lead to a more moderate rise in the use of energy.

Nevertheless, even with these more modest rates of energy growth, the per capita demand in the United States is, according to our estimates at the Institute for Energy Analysis, going to rise — from 340×10^6 kilojoules per person per year to around 400×10^6 kilojoules per person per year in the low scenario, 480×10^6 kilojoules per person per year in the high scenario. Moreover, we believe it likely that the fraction of energy that goes through electricity will also increase — from 28 percent at present to about 50 percent. This amounts to about 200×10^6 kilojoules per person per year going into electricity.

Let us set aside for the moment the question of whether this electricity will be generated primarily by nuclear energy or by coal,

and speculate on the pressure put on our coal resources if all of this electricity were produced from coal. This amounts to, say 50×10^{15} kilojoules per year from coal, which corresponds to about 2×10^{9} tons of coal per year. Now returning to Table 1, we see that at this rate we would use our reserves in 100 years and our ultimately available resource in about 500 years. These times do not consider the opposing factors that other energy sources will supplement coal for electric generation and that some coal will be used to make liquid and gaseous fuels. Nor do we take into account a likely shift toward coal as a source of industrial heat, a shift that would be encouraged if a reliable fluidized-bed boiler is developed.

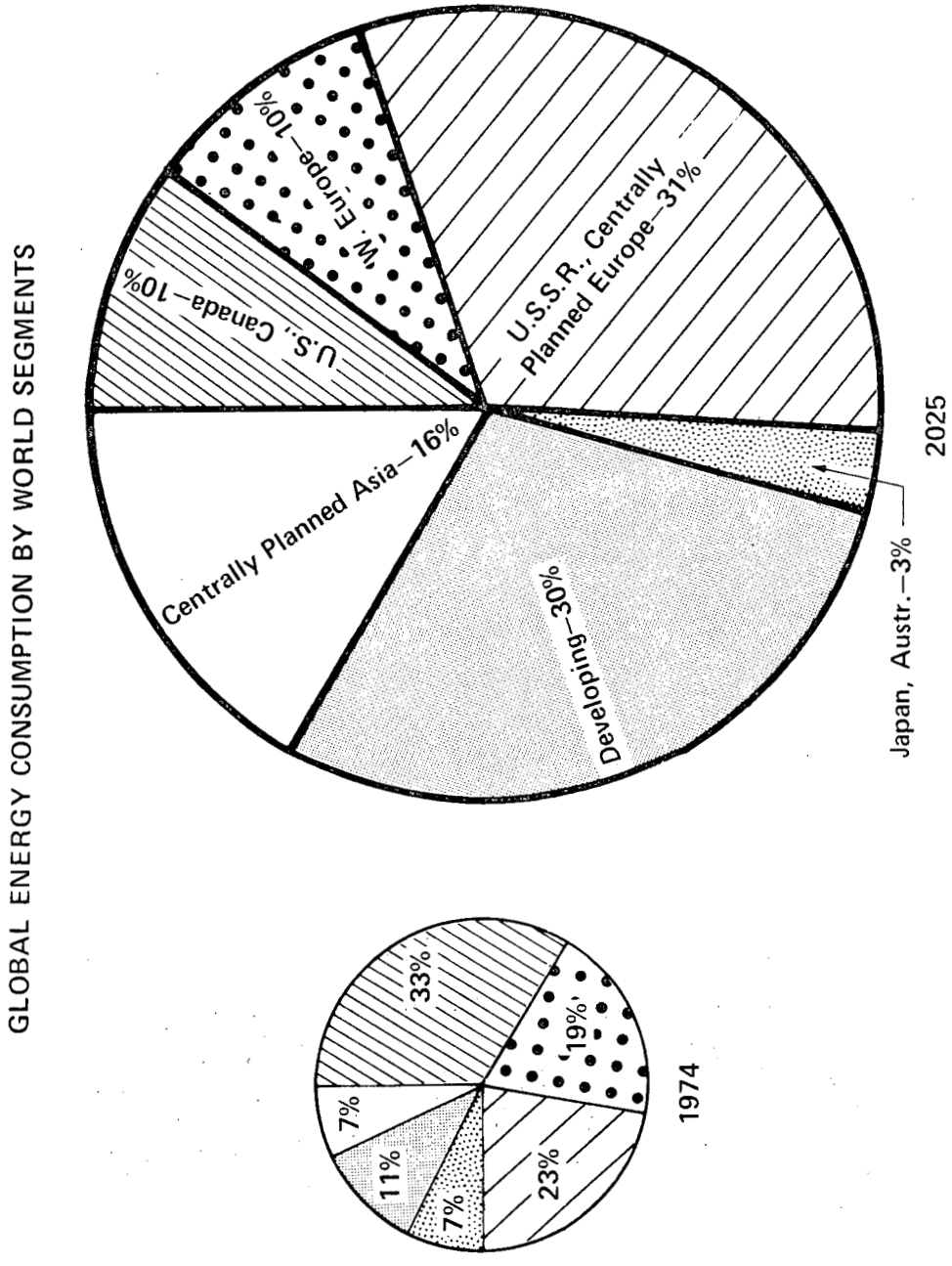
These estimated times to depletion are reassuringly long but we cannot be complacent. We have assumed that our asymptotic energy system levels off at 400×10^{6} kilojoules per person per year and 250×10^{6} population for a total of 100×10^{15} kilojoules. With equal plausibility we could consider the demand to level off at 180×10^{15} kilojoules — say 600×10^{6} kilojoules per person per year and 300×10^{6} population. In that case we might imagine coal supplying 90×10^{15} kilojoules per year, and our reserves and ultimately available resource would last, say 55 and 240 years respectively.

— World Demand for Coal —

These figures take little account of the rest of the world. R. M. Rotty has projected what the future demand for energy in a developing world might come to.[4] He divides the world into 6 regions and projects the energy growth of each independently, with the presently underdeveloped

countries expanding both their populations and their per capita energy expenditures much faster than the United States. He assumes a yearly per capita growth rate in these countries of about 3.5 percent per year and a population growth of 2 percent, which gives an overall energy growth of 5.5 percent per year (compared with 8 percent during the past decade). This leads to an average per capita expenditure in these countries about one-sixth that of the present U.S. — say 50×10^6 kilojoules per person per year by the year 2025. Rotty's estimated total world energy demand reaches about $1{,}300 \times 10^{15}$ kilojoules by 2025, distributed among countries as shown in Figure 1. If we assume 50 percent of this is supplied by coal, the world reserve and ultimately available resource would then last roughly 30 years and 140 years. But this is by no means an upper limit. F. Niehaus has proposed a scenario based on 10^{10} people using an average of 200×10^6 kilojoules per person per year for a world total of $2{,}000 \times 10^{15}$ kilojoules per year.[5] If 50 percent of this is met by coal, the depletion times are, respectively, 20 years and 90 years. Moreover, since the world's coal seems to be confined largely to the United States, the USSR, and China, such world scenarios would undoubtedly put much more pressure on U.S. coal reserves than we would estimate simply from the projections of U.S. demand alone. Indeed, there may be an inconsistency in much of our energy futurology: we usually assume that eventually the underdeveloped countries will use energy at some fair fraction of the per capita energy demand of the developed world, yet we don't really face squarely the question of where they will get their fossil fuel. Should, say, one-

FIGURE 1


GLOBAL ENERGY CONSUMPTION BY WORLD SEGMENTS
U.S., Canada—10%
W. Europe—10%
U.S.S.R., Centrally Planned Europe—31%
Centrally Planned Asia—16%
Developing—30%
Japan, Austr.—3%
2025
33%
19%
7%
11%
7%
23%
1974

fourth of the world's energy be derived from U.S. coal — this proportion is the same as the U.S. coal reserve compared to the world reserve — and if the world's energy demand reaches 1,300 x 10^{15} kilojoules, the United States would have to supply some 13 x 10^9 tons of coal per year. This seems like an astronomical amount of coal.

Obviously such numerology cannot be taken fully seriously. Nevertheless, we would claim that the world's coal resource of 15 x 10^{12} tons, which seems so enormous compared to the present use of coal at the rate of 3 x 10^9 tons per year (1973), may be a far smaller usable resource than the raw estimates suggest.

— Ultimate Climatic Limits on the Use of Coal —

The atmosphere contains about 710 x 10^9 tons of carbon in the form of CO_2. This corresponds to a concentration of 330 parts per million (ppm). There is some evidence that about one-half the CO_2 injected into the atmosphere by the burning of fossil fuel remains there. In Table 2 we give the concentration of CO_2 in the atmosphere if each of the coal reservoirs as well as the world's oil and gas are burned and one-half the released CO_2 remains in the atmosphere.

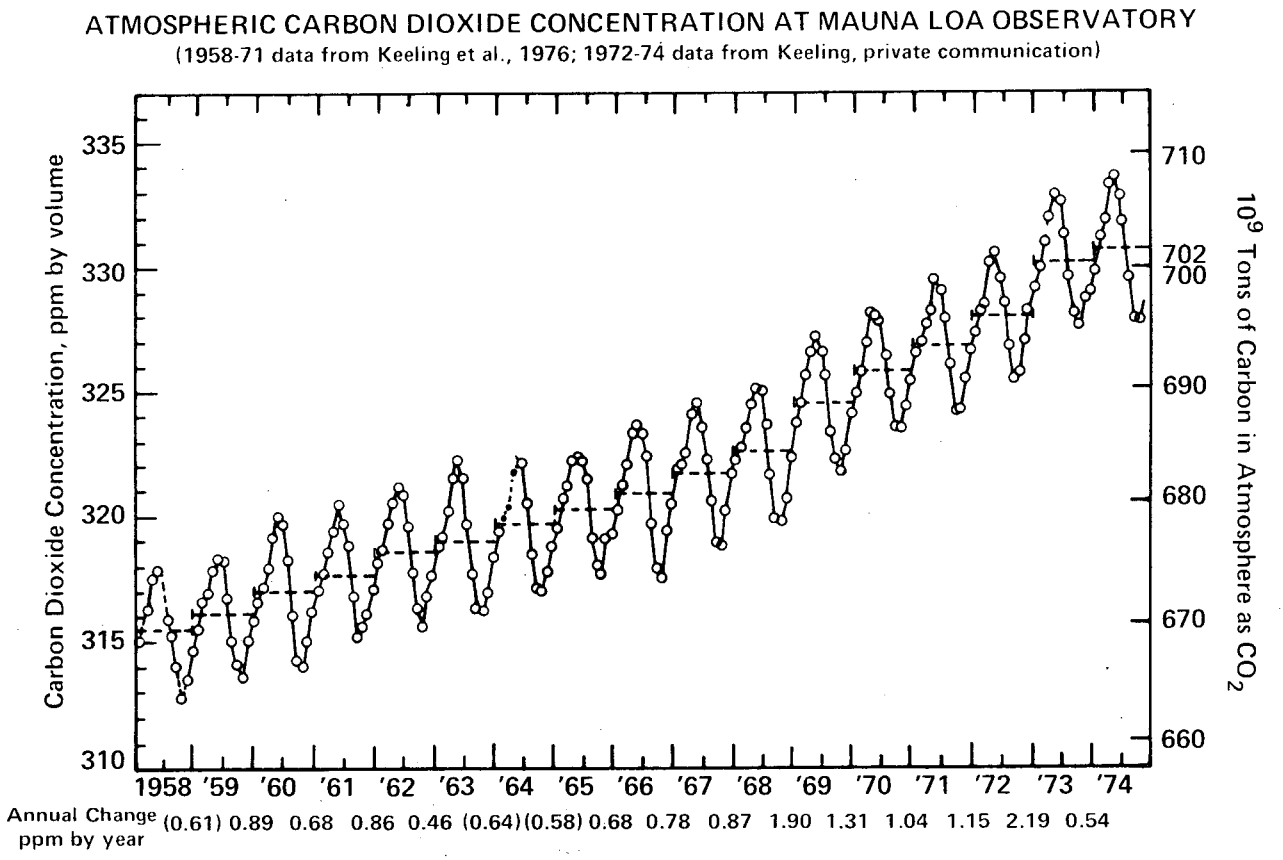
The carbon dioxide burden in the atmosphere has been increasing at a rate of about 1 ppm per year, at least for the 20 years since accurate monitoring of CO_2 began (Figure 2). To be sure, during this period tropical forests have been cleared, and there is controversy as to the extent to which the decay and burning of this wood have contributed to the present CO_2 burden. At the recent ERDA-sponsored workshop on the

TABLE 2. PROJECTED ATMOSPHERIC CO_2 CONCENTRATION FROM FOSSIL FUEL CONSUMPTION IF HALF OF THE RELEASED CARBON REMAINS IN THE ATMOSPHERE

Fuel Burned	Carbon Retained in the Atmosphere (10^9 tons)	Atmospheric Concentration CO_2 (ppm)	Years at Asymptotic Level
Present concentration	710	330	
Reserve	285	460	30
Reserve base	570	600	60
Ultimately available	1,365	960	140
World resources	5,225	3,760	550
Oil	125	390	
Natural gas	95	370	

global effects of CO_2 in the atmosphere,[6] it was concluded that we do not really know whether the biosphere is a net source or a net sink of CO_2. On the other hand, W. Broecker presented evidence that if clearing of the biosphere is a source of CO_2, the amount of CO_2 thereby added to the atmosphere must be small compared to that contributed by burning fossil fuel. Moreover, since the biosphere contains only one-tenth as much carbon as does the world's coal resource, even if the entire biosphere were removed (an entirely implausible event) it could ultimately contribute only 10 percent as much CO_2 as would the burning of all our fossil fuel. We would conclude that the CO_2 increase is probably related to the burning of fossil fuel, and that in the long run we may encounter extremely large increases of CO_2 as a result of our use of fossil fuel.

FIGURE 2


ATMOSPHERIC CARBON DIOXIDE CONCENTRATION AT MAUNA LOA OBSERVATORY
(1958-71 data from Keeling et al., 1976; 1972-74 data from Keeling, private communication)
Carbon Dioxide Concentration, ppm by volume
335
330
325
320
315
310
710
702
700
690
680
670
660
10^9 Tons of Carbon in Atmosphere as CO_2
1958 '59 '60 '61 '62 '63 '64 '65 '66 '67 '68 '69 '70 '71 '72 '73 '74
Annual Change ppm by year
(0.61) 0.89 0.68 0.86 0.46 (0.64) (0.58) 0.68 0.78 0.87 1.90 1.31 1.04 1.15 2.19 0.54

Carbon dioxide absorbs energy in the infrared. Solar energy incident on the earth's surface is reradiated at wave lengths that can be trapped by CO_2. H. Flohn[7] estimates that the present yearly rise of CO_2 increases the energy put into the climate system by about 1.6 terrawatts.

If the use of fossil fuel increases along Rotty's projections, the CO_2 concentration would double within the next 50 to 75 years. We do not really know how the climate would change if CO_2 concentration doubled. Manabe and Wetherald,[8] with their elaborate climate model, predict a global average temperature increase on the order of 2°C and an 8-10°C increase in temperature of the pole for a twofold increase of CO_2. To be sure, the models are crude, and they do not include the effect of clouds. What estimates have been made of the effect of clouds, by Ramanathan[9] and by Schneider et al.,[10] however, suggest that clouds may not be the potent source of negative feedback we had originally hoped for.

The concentration of CO_2 in the atmosphere is more strongly tied to the utilization of coal than to that of oil and natural gas simply because the coal resource is so much larger than the oil and gas resource. The total carbon content of the world's oil and gas reserve (not counting oil shale) is about 440 x 10^9 tons; this is but 40 percent of the reserve base of coal. Thus even if all the oil and gas were burned, the CO_2 concentration would be increased only by 30 percent; whereas if coal equivalent to the reserve base is burned, the CO_2 concentration would increase by 80 percent. (These figures do not include any contribution from oil shale.) Although an increase of 15 percent, i.e., 70 ppm (which could be released by the burning of oil and gas) might be dangerous, the

potential contribution from coal is 5 to 10 times greater. This suggests that although CO_2, if it is indeed a problem, will be exacerbated by our use of oil and gas, it is the burning of the much larger reservoir of carbon in coal that must be our primary worry. So to speak, the world can burn its oil and gas without worrying too much about CO_2; it can eat into its much larger reservoir of coal only at the risk of elevating the CO_2 in the atmosphere to what may be serious, or even catastrophic, levels.

— The Choices Before Us —

Let us set aside for the moment the possibility of limits on our use of coal imposed by the CO_2 problem, or indeed, by other environmental constraints, and instead ask whether coal will be chosen on strictly economic grounds over other possible sources of energy. As a fuel for generating electricity, coal is now in direct competition with nuclear energy. D. Phung of the Institute for Energy Analysis has estimated the relative cost of electricity from coal and from light water reactors (LWR's), and his results, taken from USNM, are presented in Table 3. The relative prices of nuclear- and coal-generated electricity are sensitive to perceived rates of inflation and to assumed interest rates. Roughly speaking, since fuel costs for coal boilers are relatively more important than for nuclear reactors, whereas the situation is reversed with respect to capital costs, one would expect coal to suffer relative to nuclear energy if inflation is high, and to show up better if inflation is low. Phung's analysis bears this out; on the other hand, it is clear that nuclear energy enjoys a distinct advantage only where low-sulfur coal is unavailable. In the Mountain States, coal is cheaper than nuclear energy.

TABLE 3. EFFECT OF FUEL ESCALATION RATES ABOVE INFLATION RATE ON DIFFERENCES BETWEEN COST OF NUCLEAR- AND COAL-GENERATED ELECTRICITY

Assumptions on Net Fuel Cost Increase (per year)	Percent Electricity Cost Advantage (Disadvantage) of Nuclear Over Coal: Nuclear Over Coal Without Scrubbers	Nuclear Over Coal With Scrubbers
Coal 0%, Nuclear 0%	9	18
Coal 0%, Nuclear 2%	-1	8
Coal 0%, Nuclear 4%	-12	-4
Coal 2%, Nuclear 2%	17	24
Coal 2%, Nuclear 4%	4	10
Coal 2%, Nuclear 6%	-11	-5
Coal 4%, Nuclear 4%	26	31

Note: $\text{Percent Difference} = \frac{\text{Coal Cost} - \text{Nuclear Cost}}{\text{Nuclear Cost}} \times 100$

Base Case assumes 5 percent inflation and 11 percent operating discount rate (6 percent net discount rate).

The relative cost of nuclear- and coal-generated electricity is sufficiently uncertain that one would be hard put to insist that, over the next 30 years, nuclear energy enjoys as large an advantage as our analysis suggests. Nevertheless, if one takes our results at face value and projects the demand for coal and nuclear energy out to 2010, we come up with the figures shown in Table 4. Should a nuclear moratorium be imposed that allows no new reactor starts after 1985 but allows reactors already on line to continue operation to 2010, then the total amount of coal required in 2010 is about twice that required in the absence of a

TABLE 4. ESTIMATES OF FUTURE U.S. COAL REQUIREMENTS (FROM USNM)

(10^9 metric tons)

	1985	2000	2010
Low Demand			
Nuclear option	0.64	0.71	1.04
Coal option	0.64	1.36	2.39*
Annual percent increase (coal option)	5.1	5.8	
High Demand			
Nuclear option	0.66	1.74	2.28
Coal option	0.66	2.40*	4.36*
Annual percent increase (coal option)	9.0	6.1	

*Average tonnages for 2000 and 2010 have been increased 17 percent to account for Western coal having about three-fourths the heat content of Eastern coal [26.5 x 10^6 kilojoules/ton (22.8 x 10^6 Btu/short ton) is the average heat value used up to annual production of 2.0 x 10^9 tons].

moratorium. Thus in the case of a nuclear moratorium and a high demand, we would estimate the coal required to be almost 5 x 10^9 tons — and this does not do justice to the demand that may arise among the lesser developed countries (LDC's).

At the moment we are unclear as to when breeder reactors will be introduced in the United States. Under the circumstances the total energy that we can extract from LWR's is limited by the uranium supply; but since the latter is really not known, we can do little more than speculate as to how large their contribution to our energy system can be. Since a 1,000 megawatt-electric LWR without recycle requires about 200 short tons (180 metric tons) of uranium per year, and its heat equivalent is .06 x 10^{15} kilojoules per year, we can compute the amount of coal we can displace

with uranium in LWR's for various assumed uranium supplies. These are given in Table 5. We see that even with the low uranium supply, LWR's would displace about 20 billion tons of coal — i.e., about 10 percent of what Averitt estimates to be the U.S. coal reserve. If the highest uranium estimate proves correct, then some 82 billion tons, i.e., almost one-half of Averitt's reserve, could be used for purposes other than generating electricity.

TABLE 5. DISPLACEMENT OF COAL BY LIGHT WATER REACTOR (FROM USNM)

Uranium (short tons)	No. of 1,000 MW(e) LWR's	10^{15} kJ per Year	Total kJ (x 10^{15}) (30 years)	Tons of Coal Displaced
1.8×10^6	300	18	540	20×10^9
3.6×10^6	600	36	1,080	41×10^9
7.2×10^6	1,200	72	2,160	82×10^9

No one can say whether such displacement will occur. Although, as we see the situation now, nuclear energy appears cheaper than coal in most parts of the country, it would be imprudent to decide that economic forces will cause the large displacement of coal suggested in our Table 5.

If we look at the matter in broadest terms, we find ourselves beset with a profound dilemma. The difficulties and risks of the nuclear path have been delineated often and in detail. Of these, proliferation of nuclear weapons probably poses the greatest risk, though one must always remember that power reactors and chemical plants provide a sufficient,

not necessary, technical basis for proliferation. The major risk in the coal path is the possible CO_2 catastrophe. In a way this is the coal analogue of nuclear proliferation: it is global, uncertain, possibly catastrophic. Thus we see the dimensions of the dilemma: the two energy systems upon which we are expecting to depend, at least over the medium term, are flawed to a degree that is at present essentially impossible to fully estimate, and that indeed may never be fully possible to estimate. To those who embrace coal as a fission-free bridge to a solar future, the CO_2 question should inject a note of prudent concern: we can turn the phrase around and ask whether fission based on reactors of current design perhaps will have to serve as a coal-free bridge to a fusion, breeder, or solar future. We must also consider the possibility that both nuclear energy and coal will be judged by future generations to be fatally flawed and the question, "Can we make it on solar energy alone?" will have to be rephrased: "How can we make it on solar energy alone?"

What can we do under the circumstances? The most obvious first course is to expend much more effort in trying to understand the CO_2 question: does it or does it not pose a real threat? It is gratifying that ERDA as well as other energy research agencies throughout the world are finally addressing the question seriously. In the meantime we can do no better than to keep our options open — meaning nuclear, geothermal, solar, and coal, and to try to clarify just what we can do should the twin Swords of Damocles, one called CO_2, the other called proliferation, begin to fall upon us.

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