Health and Economic Costs of Alternative Energy Sources

by L.D. Hamilton and A.S. Manne

Before the United States of America can arrive at a coherent national energy policy, several ongoing debates must be resolved – on environmental hazards, health impacts, and the direct economic consequences of alternative future energy options. No one strategy is obviously correct – or uniquely ethical. Each strategy has its drawbacks, each can be blocked by one or another coalition of interest groups.

The public is poorly informed by the media. A single large coal-mine accident is far more extensively reported than a long series of isolated accidents at grade crossings for coal trains, and yet the latter causes more deaths each year. Similarly, the public debate on nuclear issues is focused on low-probability, high-consequence events. It is as though national policy were being framed by a gambler whose motto is "it's only the stakes and not the odds that matter".

The two authors of this paper come from different disciplines, yet we both believe that the odds *do* matter. It is essential that the public be well informed about the health risks and the economic consequences of a moratorium on the civilian uses of nuclear energy in the USA. We think that such a moratorium would adversely affect health and the economy, These impacts – although small in relation, say, to the overall death rate or to the overall gross national product – are not small in an absolute sense The adverse consequences of a moratorium are much more certain, and surely outweigh the impacts of any plausible accident associated with the operation of power reactors.

In an area as new and controversial as this one, we do not claim high precision for our estimates The health effects of fossil electric plants have been studied for years, yet there are still those who are unconvinced by the evidence on the adverse health effects of such plants Refs. [1–3]. The situation here closely parallels the debate on the hazards of cigarette smoking. Although it is now established beyond reasonable doubt that cigarette smoking does cause an immense incidence of cancer and heart-disease, we still do not know the final chemical nature of the active carcinogens or the inducers of cardio-vascular damage Similarly, in the case of fossil or nuclear electric plants, we must rely upon indirect reasoning Epidemiological, meteorological, and air chemistry models are by no means as clear-cut as laboratory experiments, yet these models are the only means available today of estimating the relative hazards of alternative energy sources

We shall not examine either solar electric or thermonuclear fusion power in any detail The former is not yet cost-competitive, and the latter has not yet been proven to be technically feasible Neither of these sources is likely to be significant until the 21st century

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THE 'BEAD' MODEL FOR HEALTH IMPACT ASSESSMENT

National energy policy requires genuine totalling of *all* costs in assessing energy alternatives – human, environmental, short-range and long-range as well as easily quantifiable economic costs The Biomedical and Environmental Assessment Division (BEAD) at Brookhaven aims at such a real costing. All forms of energy, including that from new technologies, are being assessed Beginning with a compilation of residuals (resources consumed as well as the pollutants) from the energy system, the various pathways to man are traced and health effects gauged. The programme integrates information produced by research on effluents, control technology, transport of pollutants, meteorology, ecology, and on a diversity of laboratory programmes on biological and medical problems. (This integrated assessment interlocks with a broad range of national energy modelling and policy analyses now carried out by the several energy technology and economic analysis groups at Brookhaven's National Center for Analysis of Energy Systems.)

BEAD has developed methods to analyse effects of the energy system [4] Each stage in the fuel cycle for electric power generation from coal, oil, natural gas, hydroelectric and nuclear, has been characterized by a series of effects – consequences – modules Thus, surface mining of coal results in (a) particulates and noise in air, and (b) acid, dissolved solids, etc., in water Central power conversion of coal results in particulates, SO_2, NO_2–HC, etc., in air The effects modules describe how an emission or resource use affects water, air, land, materials and biota The modules may thus apply to different stages of the same fuel cycle and also be common to different fuel cycles For analysis, the modules are composed of vectors defining a chain of effects resulting from an initial emission or resource use. Each module depicts an environmental stress imposed by a component of a fuel cycle or another module component of a fuel cycle. Ideally, each of the individual vectors within a module will be quantified

While we strive to integrate health effects, making use of various approaches and converging data bases, decision-makers need assessment *now:* delayed decision can be very costly, and in many instances decision cannot be delayed Our guidance on health effects of existing and proposed energy technologies must be prompt That is why we have estimated in a simplified way the health effects of power plants We have used published – and soon to be published – assessments of various sources, and a simplified relationship between air pollution and health effects.

In calculating the health effects of air pollution from fossil-fuel power plants, one must specify which pollutants result in morbidity and mortality These include SO_2, total suspended particulate matter (TSP), polycyclic hydrocarbons and other organics, nitrogen oxides, ozone, and other secondary products Knowledge is insufficient to relate each independently to health The effects of these pollutants are being quantified in studies on animals, organisms and plants; in studies on man; in populations occupationally exposed to high levels of mixtures of pollutants, and in epidemiological studies of general populations similarly (although usually less) exposed. Exact estimates of the hazards await definition of precisely how damage is done. In the meantime, quantification of health effects must rely on existing epidemiological studies on general populations These epidemiological studies have usually used one or another of the pollutants as an index of exposure to air pollution as a whole Assessments based on these studies therefore inevitably contain additional uncertainties, since the mix of pollutants varies from place to place, i e. use of one pollutant as an index of damage in one place may not quite apply to another. This is particularly true when the index itself is a pollutant, e.g. TSP, whose composition may vary

Most epidemiological studies show good correlation between TSP and health effects The correlation between SO_2 and health effects is less sharp, and it has been difficult to show correlation between impaired health and nitrogen oxides or oxidants. Nitrogen oxides and oxidants, however, have shown measurable biological damage in laboratory studies [5].

While experiments exposing animals to SO_2 gas have not clearly supported epidemiological findings [6], particulate sulphates, chemical transformants of SO_2, have been shown by both animal and epidemiological studies to be a major cause of disease [7]. Particulate air pollution from large modern coal and oil power plants is composed primarily of these active transformants. Due to the common use of high-efficiency particulate removal equipment, the main exposure of populations to particulates from fossil power plants is due to secondary formation of sulphate particulates. The proportion of sulphates in TSP in the power-plant plume may be as high as 98%, leading us to concentrate on use of TSP and sulphates as *indices* of air pollution.

If one calculates the health effects of power-plant pollution from TSP data -- these data having been gathered from populations exposed in urban areas where sulphates constitute only about 15% of TSP — one badly underestimates the health effects. In fact, assuming that the disease-producing agents in TSP are sulphates, one would need to use a correction factor on dose-response effects of TSP calculated from urban areas.

BEAD's standard 1000-MWe plant is on a plain, and air-pollution emission rates are determined from assumptions as to plant, fuel characteristics, and emission-control devices. The input components of the air-pollution model are detailed elsewhere [8—10]. A wind-rose meteorological model, coupled with an air chemistry model based on a linear SO_2—SO_4 conversion rate, is used to determine ground-level exposures within an 80-km radius around the power plant.

Use of a linear SO_2—SO_4conversion rate is the only atmospheric chemistry incorporated in the analysis at this time. Use of only one index of pollution — sulphates — is undoubtedly too simple a way to index the health hazard of air pollution. Finally, because of lack of knowledge of the exposure-response curve, particularly at low levels of air pollution, we have assumed a linear dose-effect relationship, as is common in estimating radiation risks.

As we are considering the effects of small increments on background levels of air pollution close to clinically effective doses, the error in this assumption is likely to be less than that involved in extrapolating from high to low doses of radiation. Even if the exposure-response curve is not linear, it is probable that the levels which we are considering do not fall far outside the linear portion of the curve.

Increased total mortality rate is the "health impact" used here Two studies, one intercity (Lave), the other intracity (Winkelstein), provide strong evidence of an association between annual average air pollution levels and increased mortality rates [11, 12]. Other studies also support this association, but they are not suitable for derivation of quantitative dose-response functions [13, 14]. We therefore derived dose-response functions from the Lave and Winkelstein data.

Table 1 shows the increased mortality within 80 km expected from various technological and population alternatives due to air pollution from a 1000-MWe fossil-fuel power plant.

Table 1. Excess mortality due to air pollution exposure from 1000-MWe fossil-fuel power plant within 80 km

(305-m stack height; 75% capacity factor)

	No of annual excess deaths				
	Lave[a]			Winkelstein[a]	
	Lower 10%	Median	Upper 10%	Linear	Non-linear
Eastern high-sulphur coal (2 9 X 10^7 J/kg coal, 3% sulphur) (1 25 X 10^4 Btu/lb)[b]					
No sulphur removal					
3 X 10^6 people within 80 km	0	20	100	130	450
0 7 X 10^6 people within 80 km	0	4 6	23	31	105
90% sulphur removal					
3 X 10^6 people	0	2	10	13	45
0.7 X 10^6 people	0	0 5	2 3	3 1	11
Eastern low-sulphur coal. (2 9 X 10^7 J/kg, 0 4% sulphur) (1 2 X 10^4 Btu/lb)					
No sulphur removal					
3 X 10^6 people	0	2 7	13	18	60
0 7 X 10^6 people	0	0 6	3 1	4 1	14
Montana coal (2 1 X 10^7 J/kg, 0 8% sulphur) (8 6 X 10^3 Btu/lb)					
No sulphur removal					
3 X 10^6 people	0	7 3	37	49	170
0 7 X 10^6 people	0	1 7	8 6	11	39
High-sulphur oil (4 6 X 10^7 J/kg, 2 5% sulphur) (2 X 10^4 Btu/lb)					
No sulphur removal					
3 X 10^6 people	0	10 4	52	70	236
0.7 X 10^7 people	0	2 4	12 2	16	55
Low-sulphur oil (4 6 X 10^7 J/kg, 0 2% sulphur) (2 X 10^4 Btu/lb)					
No sulphur removal					
3 X 10^6 people	0	0 8	4.2	5 6	19
0 7 X 10^7 people	0	0 2	1 0	1 3	4 4

[a] Modified from data of Lave and Winkelstein For technical details, see Ref [9]

[b] 1 Btu = 1 054 X 10^3 J

Table 2. Estimated health effects in 1975 associated with production of electric power

Fuel	1975 (kWhe $\times 10^9$)[a]	Equivalent No 1000 MWe plants	Estimated deaths	Estimated disabilities
Coal	844	128	1900–15 000	25 000–39 000
Oil	292	44	88–4400	4000–7900
Gas	297	45	6	600
Nuclear	168	26	18–42	130–470
Totals	1601	243	2000–19 000	29 000–48 000

[a] Preliminary Source Ref [15]

The data from Table 1 were combined with estimates of morbidity and mortality produced by the fuel cycles necessary to sustain a 1000-MWe power plant for one year, to calculate the health effects associated with the production of electric power in the USA in 1975. These data are summarized in Table 2. From this, one derives the estimated health effects in 1975 associated with a total fuel cycle standardized to produce 10^{10} kWh electric power:

From coal estimated deaths 10–200,
estimated disabilities 300–500,
From oil estimated deaths 3–150,
estimated disabilities 150–300,
From gas: estimated deaths 0.2,
estimated disabilities 20,
From nuclear. estimated deaths 1–3,
estimated disabilities 8–30.

On an actuarial basis, reactor accidents contribute only 0.02 deaths per GWe-year. These are high-consequence but low-probability accidents.

For perspective, the approximate annual total deaths in the USA are 2×10^6, the percentage associated with electricity production is 0.1–1.0. Approximate deaths in the USA, ages 1–74, are 1.1×10^6; the percentage associated with electricity production is 0.2–1.9. Air pollution from fossil fuels is by far the largest contributor to deaths. This may be compared with other known causes of death in the USA: ~ 17% of deaths associated with smoking, ~ 5% with car accidents (half of which were due to drunken drivers), and ~ 5% due to iatrogenic lethal treatment.

THE ETA-MACRO MODEL FOR ECONOMIC AND TECHNOLOGICAL ASSESSMENT

To arrive at an overall view, health effects must be integrated with many other factors. The next step then is to take account of economic and technological considerations. For this purpose, it has proved convenient to employ the ETA-MACRO model. This represents a merger between ETA (a process analysis for energy technology assessment) together with a macro-economic growth model providing for substitution between capital labour and energy inputs [16–17].

ETA-MACRO is a tool for integrating long-term supply and demand projections. It is designed to compare the options that are realistically available to the USA as we move away from our present heavy dependence upon oil and gas resources towards a more diversified future energy economy.

To account for the eventual exhaustion of today's fuels, the model operates with an unusually long time horizon – through the middle of the 21st century. To avoid a cumbersome amount of detail, the emphasis is upon nation-wide trends rather than those within individual regions. The focus is upon the time period after 1990, which is the era when we are likely to begin a major transition to new supply sources. Clearly, a long-term perspective multiplies the uncertainties and the sheer guesswork involved in any technology assessment. Nonetheless, this long-term view seems essential if we are to make prudent decisions *today* for technologies which have inherent lead-times of 10–20 years, and which are then likely to operate over a service life of 30 years. ETA-MACRO allows explicitly for

(a) Energy-economy interactions. the prospect that rising energy costs and limited supplies will prevent the economy from achieving its full potential gross national product growth rate, and that this in turn will slow down future capital accumulation.
(b) Cost-effective conservation: rising prices will reduce energy demands below the amounts projected from historical trends.
(c) Interfuel substitution: changing conditions will induce consumers to replace oil and gas by electricity, e.g. heat pumps in place of fuel burners.
(d) New supply technologies: synfuels, nuclear and solar power, each with its own difficulties and uncertainties on dates and rates of introduction

The model simulates a market economy over time – assuming that producers and consumers are sufficiently farsighted to anticipate future scarcities. Supplies, demands and prices are matched through a dynamic *non*-linear programming model. The higher that prices rise, the greater the amounts of future supplies that are likely to become available, and the greater will be the inducements for consumers to conserve energy

All costs and benefits are expressed in terms of "real" US dollars of 1975 purchasing power. Thus, any price rises due to general inflation do not affect the analysis For the most part, the numerical assumptions have been those adopted by the CONAES MRG (Modelling Resource Group, Committee on Nuclear and Alternative Energy Systems, National Academy of Sciences). These ground rules imply distinctly lower growth rates of energy demand than indicated in previous reports on the ETA model. Even with the CONAES MRG assumptions, however, there could be substantial economic costs if the USA were to adopt a "no nuclear" policy.

The costs of such a policy depend largely on what is assumed with respect to coal, for coal represents the most immediate alternative to nuclear power in the USA. To allow for the possible health, environmental and global climatological consequences of extensive use of coal, the MRG defined an upper bound upon the annual rate of this fuel consumed for all purposes taken together: coal-fired electricity, direct uses and synthetic fuel. It was postulated that this upper bound would take the form of an S-shaped "logistic" curve defined by three points: the actual 1970 value of 13 quads, a projected bound of 40 quads for the year 2000, and a long-term asymptote of 50 quads. Admittedly, this is an area of great uncertainty. It is a topic on which there is much room for collaboration between environmentalists, health scientists, economic analysts and engineers. We hope that our calculations will encourage others to undertake further research in this area.

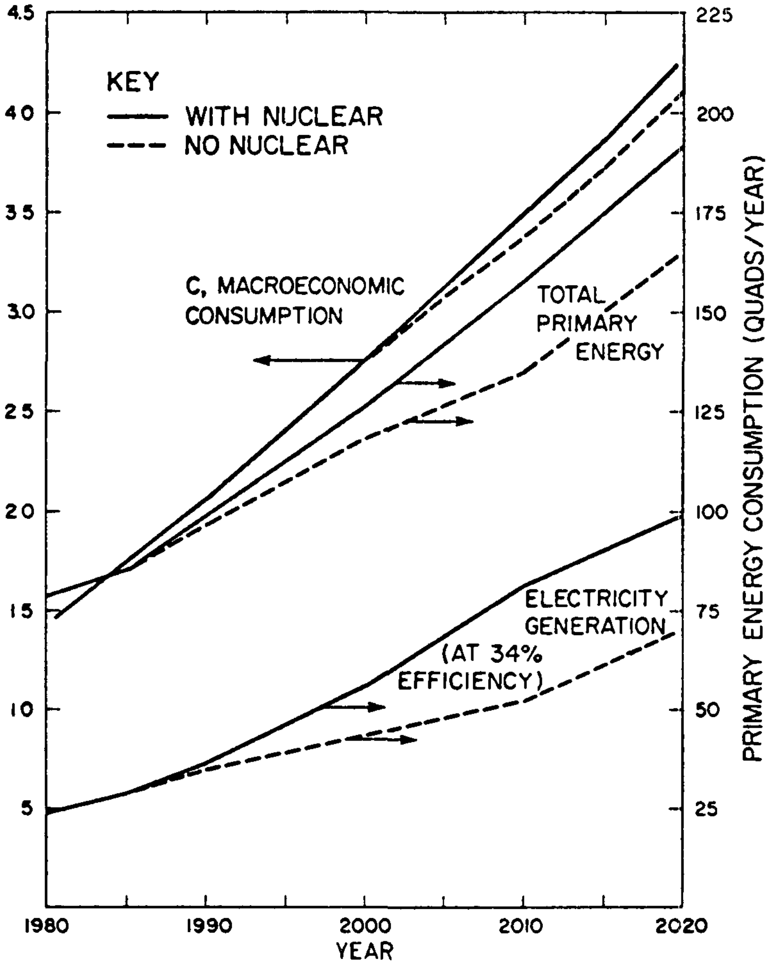

Figure 1: Base case results.

Under base-case assumptions, it turns out that coal would *not* be a binding constraint until after the year 2000, and that the economy would therefore be unaffected by a "no nuclear" policy until that date (see Fig 1). After the year 2000, the MRG ground rules provide that solar electricity is available as a "backstop" technology – but with levelized costs that are 20 mills/kWh higher than coal or nuclear (see Tables 3, 4 and 5). Adding together the direct and indirect consequences of high-cost solar energy and of other alternative energy systems, it turns out that the total losses in aggregate consumption are US $109 X 10^9, or 3.1% of aggregate consumption in 2010 (see middle column of Table 6). Adding over all years from 1975 through 2050, the present value of these losses would be US $77 X 10^9 or US $595 X 10^9, depending on whether public decisions are to be based on a 10% or a 5%

Table 3. Cost assumptions for economic comparison of baseload plants at 65% capacity factor (1975 general price level)

Type of electricity plant	Coal-fired	LWR	FBR	Solar electric
Capital costs (US $/kW)	520	650	810	1730
Unit costs (mills/kWh)				
Operating and maintenance	3.0	2.0	2.0	2.0
Fuel costs	7.1	4.9	2.1	0
Levelized capital costs[a]	12.2	15.2	19.0	40.5
Total	22.3	22.1	23.1	42.5

[a] Capital recovery factor based on 13%/a discount rate, 65% capacity factor and 30-year service life Therefore $(0.1334/a)\ \{cap_i \div 0.65\%\ (8.76\ 10^3\ h/a)\} = 0.0234\ cap_i$

Table 4. Cost assumptions for economic comparison of alternative sources of non-electric energy (1975 general price level)

Unit costs of PETG[a] equivalent.	PETG	Coal-based synthetic fuels	Non-electric AES[c]
US $/mm Btu[b]	2.0 (2720 quads of resources, including imports)	3.7	5.0

[a] Petroleum and natural gas
[b] 1 Btu = 1.054 X 10^3 J
[c] Alternative energy system.

discount rate. Note that the macro-economic losses are low initially and that they rise rapidly after the year 2000. This is why a 5% discount rate implies that the present value of these losses would be far higher than twice those associated with a 10% rate.

The preceding results have been based on 0.25 as our best estimate of σ, the "elasticity of substitution". This parameter measures the ease or difficulty of substituting other economic inputs in place of energy. With $\sigma = 0.25$, this means that a 10% rise in the relative price of energy will lead to a 2.5% decline in the optimal consumption of energy relative to other economic inputs such as capital and labour. There is a wide margin of uncertainty in any econometric estimates of σ With a higher elasticity of substitution, the macro-economic impact of a "no nuclear" policy would be lower than indicated by the base case. If, for

Table 5. ETA-MACRO Base Case

	1985	1990	2000	2010	2020	2030
1 DOMESTIC ENERGY PRODUCTION, BY SOURCE NET OR EXPORTS (QUADS)	66.6	78.1	105.1	142.3	185.6	229.5
1.1 COAL. TOTAL	17.9	21.2	28.7	45.0	47.7	49.0
A. FOR ELECTRICITY GENERATION	12.4	15.1	21.3	24.5	18.5	9.4
B FOR SYNTHETIC FUELS	— —	0.0	0.0	11.5	18.2	26.2
C DIRECT USE AND OTHER	5.5	6.1	7.4	9.0	11.0	13.4
1.2 NATURAL GAS, OIL AND NGL	36.5	39.8	42.1	31.6	13.4	5.0
1.3 NUCLEAR, TOTAL	8.3	12.7	27.1	48.1	70.1	95.3
LWR	8.3	12.7	27.1	46.5	47.7	33.3
FBR	— —	— —	0.0	1.6	22.3	62.0
1.4 SOLAR ELECTRIC	— —	— —	0.0	0.0	0.0	0.0
1.5 SHALE OIL	— —	— —	1.5	5.6	9.6	11.5
1.6 HYDRO GEOTHERMAL ETC	3.9	4.4	5.7	7.2	9.3	11.9
1.7 NON-ELECTRIC AES	0.0	0.0	0.0	4.9	35.6	56.8
2 OIL AND GAS IMPORTS (QUADS)	18.2	19.9	21.1	15.8	6.7	2.5
3 TOTAL ENERGY CONSUMPTION (QUADS)	84.9	98.0	126.2	158.1	192.3	232.0
4 ELECTRICITY GENERATION (TRILLION KWh)	2.9	3.6	5.6	8.1	9.9	11.7
4.1 % OIL AND GAS	14.7	9.0	1.9	0.0	0.0	0.0
4.2 % COAL	43.6	43.5	39.7	31.8	19.7	8.4
4.3 % NUCLEAR	28.4	35.3	48.3	59.3	70.9	81.4
4.4 % OTHER	13.3	12.2	10.1	8.9	9.4	10.2
5 URANIUM CONSUMPTION (MILLION TONS OF U_3O_8, CUMULATIVE FROM 1975)	0.2	0.4	1.0	2.1	3.5	3.7
6 DOMESTIC PRICES						
6.1 COAL ($/MM BTU)	0.7	0.7	0.7	1.5	1.5	1.5
6.2 OIL AND GAS ($/MM BTU)	2.2	2.4	3.3	5.0	5.0	5.0
6.3 ELECTRICITY (MILLS/KWh)	21.7	22.0	22.1	24.2	24.6	25.8
6.4 URANIUM ($/LB U_3O_8)	30.7	31.3	34.4	44.5	75.7	141.2

Table 6. MACRO-Economic results – three alternative elasticities of substitution

Elasticity of substitution		0.50	0.25	0.15
Supply constraints		(same as base case)	(base case)	(with additional supply constraints)
Aggregate consumption in 2010 (US $ X 10^9 at 1975 price level)	With nuclear	3566	3496	3245
	No nuclear	3552	3387	2799
Reduction in consumption in 2010	(US $ X 10^9)	14	109	446
	(%)	0.4%	3.1%	13.7%
Public discount rate.	Present value of reduction in consumption, 1975–2050 (US $ X 10^9)			
5%		293	595	3089
10%		36	77	456

example, it is assumed that $\sigma = 0.50$, the macro-economic impact is barely discernible until 2000. In this case, energy demands would grow more slowly, oil and gas resources would become exhausted less rapidly, and there would be more time for a transition to future high-cost alternative energy sources. Price-induced conservation would solve our energy problems for the next 50 years – if it turns out that $\sigma = 0.50$ or higher.

With a sufficiently low elasticity of substitution, however, there could be major economic impacts from tight energy supplies. To illustrate this possibility, we have computed one set of cases in which $\sigma = 0\ 15$ (instead of the base case value of 0.25). In addition, the following reductions (or cost increases) have been made in the supplies of non-nuclear energy.

(a) The upper bound on coal consumption is reduced to 25 (instead of 40) quads in the year 2000, and the asymptote is reduced to 40 (instead of 50) quads;
(b) No shale oil resources are developed because of air and water quality constraints,
(c) The introduction date for large-scale direct solar electricity is delayed from the year 2000 to 2020, and
(d) AES (alternative energy system) costs are equivalent to oil and gas at US $8 instead of US $5 per million Btu[1].

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[1] The AES (alternative energy system) was postulated by the CONAES MRG as a backstop technology for producing clean non-electric energy Solar heating and cooling would be one example of such a backstop Other possibilities would include in-situ shale oil retorting, biomass conversion, solar-generated hydrogen, and unconventional petroleum resources Under base-case assumptions, the AES does not become a significant energy source until 2010 or thereabouts (see Table 5). For 2010 and subsequent years, the AES introduction rates appear to be on the high side These rates are probably more optimistic than those adopted by the MRG for better understood technologies such as synfuels and the breeder

Even under these unfavourable circumstances, aggregate economic activity would be only moderately affected if nuclear energy is available. In the year 2000, for example, there would be virtually no difference in total consumption With a "no nuclear" policy, however, the economic losses would be enormous. They would amount to US \$132 X 10^9 in the year 2000, and would grow to US \$446 X 10^9 in 2010 (see last column of Table 6). This would mean a 13.7% reduction of consumption in the latter year At a 5% discount rate, the present value of the reduction in consumption would be US \$3089 X 10^9 over the years 1975–2050. It would take an unlikely combination of circumstances to produce these results, but this combination seems far more likely than some of the low-probability high-consequence disasters that have been discussed in connection with nuclear energy.

CONSEQUENCES OF A NUCLEAR MORATORIUM

In this concluding section, we shall indicate how the BEAD and ETA-MACRO models may be employed jointly to analyse issues such as the consequences of a nuclear moratorium. Each model is aggregated in a different way. BEAD is regionally disaggregated in order to estimate health effects, whereas ETA-MACRO is nationwide in scope. We shall see that these two models complement one another. Each improves insights into the results obtained through the other

We begin by summarizing the results of ETA-MACRO for a single point in time: the year 2000. In Table 7, note that there is a significant difference in total coal consumption as of this date 28.7 quads if nuclear energy is available and 40.0 quads if no nuclear plants are installed after 1975.

Among those supply and conservation options that are available, ETA-MACRO automatically selects the least-cost combination. With nuclear energy available, it is optimal to use up oil and gas resources at a slower rate, even though a greater total amount of energy is consumed (126.2 quads versus 118 0 quads) in the year 2000. Note that hydroelectric, geothermal, shale oil and coal-based synthetic fuels production are unaffected, and that the major differences appear in the sources of electricity generation The 450 GWe reduction in nuclear electricity is offset by only a 200-GWe increase in coal-fired plants.

We now use the BEAD model to examine the regional health impacts of these additional 200-GWe of coal-fired electrical capacity. To apply this model to these issues, we begin with Table 9 the region-specific health effects for each of the 200 additional coal fired plants that would be needed during a nuclear moratorium. These plants have been assigned to each of nine geographic regions in proportion to the population increase that is expected between 1970 and the year 2000 (OBERS residential population projections). It was assumed that the additional coal would all be strip-mined low-sulphur western coal, and that a combination of low-sulphur coal precombustion treatment with flue-gas desulphurization would result in sulphur emissions equivalent to that from 0.5% sulphur coal with a heating value of 12 500 Btu/lb[2]. Transport-associated deaths reflect accident deaths (primarily crossing accidents) for rail transport on a t/mile basis using the distance from each region to western coalfields.

For the nation as a whole, BEAD indicates that these 200 plants would lead to between 1500 and 18 000 additional deaths in the year 2000 – principally through air pollution (see Table 8). These would occur statistically; none would be newsworthy individually. In the aggregate, this impact is of the same order of magnitude as has been estimated by

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[2] 1 Btu = 1.054 X 10^3 J

Table 7. Energy supplies and demands, year 2000
(Unit: 10^{15} Btu of primary energy[a] – fossil fuel equivalent)

	Base case, with nuclear		No nuclear installed after 1975	
	Electricity[b]	Non-electric energy	Electricity[b]	Non-electric energy
Petroleum and natural gas		63.2		69 3
Shale oil		1.5		1.5
Hydroelectric, geothermal, wind, refuse, etc	5.7		5.7	
LWRs	27.1 (=475 GWe)		1.5 (=25 GWe)	
Coal	21.3 (=375 GWe)	7.4	32.6 (=575 GWe)	7.4
Totals	54.1	72.1	39 8	78.2

[a] 1 Btu = 1 054 X 10^3 J
[b] Based on 34% thermal efficiency and a 65% capacity factor Therefore 10^{15}Btu/a = 17 6 GWe

Rasmussen for a single reactor accident. The only difference is in the odds. The deaths from the 200 coal-fired plants would occur year-in and year-out. Those from a rare core-melt accident would be a one-in-a-million chance.

Table 8 shows the dose-response functions derived from Lave and Winkelstein on a unit plant basis for each region.

Table 9 extends the results to the 200 plants required to replace nuclear electricity in the moratorium. The first two columns give population increases in each region from 1970–2000, the third column gives the distribution of the 200 plants in proportion to population growth in each region, and the last five columns give the total annual excess deaths, derived from the five estimates in Table 8, from these additional plants. As already noted, the total annual excess deaths range from ~ 700, if the unlikely assumption is made that air pollution effects are zero, to the more probable ~ 1500–18 000 figures. The total projected population in the USA in 2000 is ~ 263 X 10^6 and thus the approximate annual total deaths will be 2.6 X 10^6. The upper limit of annual excess deaths would thus correspond to ~ 1% of the annual death rate. Since the meteorological model used in these estimates is confined to an 80-km radius round the power plant (in reality, of course, sulphates travel much further), the estimated air pollution fatalities in Tables 8 and 9 are probably low. Consideration of the health impact of long-distance transport of sulphate might increase them by a factor of three [18] to ten [19]. Moreover, these numbers include only mortality and not morbidity. Air pollution morbidity is estimated to be about five times the mortality figures.

Table 8. Coal plant effects by Region – 1970

1000 MWe, 0.5% sulphur, 2.9 X 10^7 J/kg (12 500 Btu/lb)

Region***	1970 Pop * X 10^6	Air pollution annual excess deaths** (1)	(2)	(3)	(4)	(5)	Strip-Mine Deaths	Rail-road Deaths	Total annual excess deaths** (1)	(2)	(3)	(4)	(5)
NE	5.23	0	5.8	29	39	131	0.1	3.1	3.2	9	32	42	134
MA	7.07	0	7.8	39	52	177	0.1	2.6	2.7	11	42	55	180
ENC	2.88	0	3.2	16	21	72	0.1	2.0	2.1	5.3	18	23	74
WNC	0.08	0	0.09	0.4	0.6	2	0.1	0	0.1	0.2	0.5	0.7	2.1
SA	2.50	0	2.8	14	19	63	0.1	2.6	2.7	5.5	17	22	66
ESC	0.77	0	0.8	4.3	5.7	19	0.1	1.7	1.8	2.6	6.1	7.5	21
WSC	0.74	0	0.8	4.1	5.5	19	0.1	3.6	3.7	4.5	7.8	9.2	23
MT	0.14	0	0.2	0.8	1.0	3.5	0.1	0	0.1	0.3	0.9	1.1	3.6
PAC	0.50	0	0.6	2.8	3.7	13	0.1	4.0	4.1	4.7	6.9	7.8	17

* This is the average population w/in 80 km for the plant sites in the Morgan/Morris 100-plant data base, except for WSC and PAC for which there are no plant sites in the data base. An average ratio of population within 80 km of the average plant site to the average population density of the census region was found for the other seven ragions. The population within 80 km of a site in WSC and PAC were estimated by applying this ratio to the regional population density.

** Estimates are (1) Tenth percentile estimate from Lave data
(2) Median estimate from Lave data
(3) 90th percentile estimate from Lave data
(4) Linear estimate from Winkelstein data
(5) "Linearized" non-linear estimate from Winkelstein data. Assuming 78.4 $\mu g/m^3$TSP base, sulfates three times as effective as TSP, $6,000 annual family income.

*** See Table 9 for explanation of region initials

Table 9. 200 Plants assigned by relative population increase

Region	1970-200 Pop increase 10^6	%	Number of plants assigned	Yr 2000 (1)	Total annual excess deaths* (2)	(3)	(4)	(5)
New England	3.116	26	11 2	45	127	451	592	1889
Middle Atlantic	8 505	23	30 6	102	414	1582	2072	6781
East North Central	9 88	24	35 5	93	233	793	1013	3258
West North Central	2 169	13	7 8	0 9	1 8	4 4	6.3	18
South Atlantic	13 618	43	49 0	189	386	1191	1541	4624
East South Central	3 483	26	12 5	28	41	96	118	331
West South Central	4 197	21	15 1	68	83	143	168	421
Mountain	2 539	29	9 1	1 2	3.6	11	13	43
Pacific	8 089	30	29 1	155	178	261	296	643
TOTAL	55 596		200	682	1467	4532	5819	18008

* See Table 8 for explanation of the basis of each estimate
The exposed population is assumed to increase in proportion to the increase in census region as a whole.

As already mentioned, much attention has focused on low-probability high-consequence risks associated with radioactivity releases from a potential nuclear reactor accident leading to a core meltdown. But, when the large consequences are multiplied by very low probabilities, the expected number of fatalities from the worst possible accident would add less than a single fatality to the 76—190 excess deaths associated annually with the total fuel cycles to sustain 450 nuclear plants (year 2000) We have not considered the risks of diversion of nuclear materials and of sabotage of nuclear facilities, but it is difficult to believe that such questions are insoluble or that they would outweigh the health impact of possibly 18 000 additional deaths each year.

POSTSCRIPT

Space does not permit a detailed comment on the Ford-Mitre report, *Nuclear Power Issues and Choices,* which appeared after our original manuscript was prepared On the environmental, health, and economic advantages of light-water reactors, we find ourselves in agreement with much of the Ford-Mitre report. We are also in agreement with their conclusions on plutonium-reprocessing plants in the hands of individual non-weapons countries. Such plants constitute an "attractive nuisance" and they do little to slow down the nuclear arms race.

With respect to the breeder R & D issue, however, we believe that the Ford-Mitre reasoning is faulty. Their arguments are based upon a world in which coal and uranium are plentiful *outside* the United States of America. If, in fact, these resources are limited, our failure to develop the breeder is likely to stimulate others to even greater efforts at development. The USA cannot participate effectively in international safeguards programmes if it foregoes the breeder altogether. Realistically, we must recognize that countries wishing to acquire nuclear weapons can do so — at lower cost and in less time — through routes other than civilian reactor programmes.

References

[1] COMAR, C L , SAGAN, L A , Health effects of energy production and conversion, Annual Review of Energy **1** (1976) 581.
Reviews Inc (1976) 581

[2] SAGAN, L.A., Health costs associated with the mining, transport and combustion of coal in the steam electric industry, Nature **250** (1974) 107

[3] HAMILTON, L D , MORRIS, S C , "Health effects of fossil fuel power plants" (Proc Symp Population Exposures, Konxville, 1974, CONF-741018 (1974) 317

[4] (HAMILTON, L D , Ed) "The health and environmental effects of electricity generation — a preliminary report", Biomedical and Environmental Assessment Group, Upton, New York, BEAG-HE/EE 12/74, BNL Rep No 20582 (1974)

[5] COORDINATING COMMITTEE ON AIR QUALITY STUDIES, National Academy of Sciences and National Academy of Engineering, Air Quality and Automobile Emission Control, prepared for the US Senate Committee on Public Works, Washington, DC (1974)

[6] ALAIRE, Y , et al , Long-term continuous exposures to sulfur dioxide in cynomolgus monkeys, Arch Environ, Health **24** (1972) 115

[7] McJILTON, C , FRANK, R , CHARLSON, R , Role of relative humidity in the synergistic effect of a sulphur dioxide-aerosol mixture on the lung, Science **182** (1973) 503

[8] US ENVIRONMENTAL PROTECTION AGENCY, Monitoring and Air Quality Trends Report 1972, Research Triangle Park, Carolina, (1973)

[9] HAMILTON, L D , MORRIS, S C , Health Costs of Substituting Coal-Electric as Alternative to Nuclear Power in a Nuclear Moratorium, Brookhaven Natl Lab Rep BNL No 22464 (Rev. 1977).

[10] MORGAN, M G , et al , A probabilistic methodology for estimating air pollution health effects for coal-fired steam electric plants, Energy Systems and Policy (in press)

[11] WINKELSTEIN, W , et al., The relationship of air pollution and economic status to total mortality and selected respiratory system mortality in men, Arch Environ Health **14** (1967) 162.

[12] LAVE, L B , SESKIN, E P , An analysis of the association between US mortality and air pollution, J Am Stat. Assoc. **68** (1973) 284.

[13] HEWITT, D , Mortality in the London borough, 1950—52, with special reference to respiratory disease, Br J Prev. Soc. Med **10** (1956) 45

[14] PAŠIC, H , ČERKEZ, F , "The effect of air pollution on mortality in Sarajevo", Proc. Int Conf Sulleldorf, 1973.

[15] Electrical World **185** (1976) 54

[16] MANNE, A S , ETA A model for energy technology assessment, Bell J Econ Manage Sci (Autumn 1976)

[17] MANNE, A S , ETA-MACRO A Model of Energy-Economy Interactions, Dept of Operations Research, Stanford Univ. Rep (Rev 1977)

[18] HAMILTON, L.D , et al , A Perspective on the Energy Future of the Northeast Health and Environmental Impacts of Alternative Energy Futures for the Northeast, Brookhaven Natl Lab. Summary, BNL Rep No 21611 and draft (1976)

[19] HAMILTON, L.D , "US electricity through the year 2000 coal or nuclear? Alternative sources and health", in CRC Forum on Energy, Session II US Electricity Through the Year 2000 Coal or Nuclear? (BUDNITZ, R T , Ed), CRC Press Inc , Cleveland (1977)

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