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Economic Assessment of Coal-fired & Nuclear Power Generation in the Year 2000

–Equal Health Hazard Risk Basis–

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2000년대 원자력과 유연탄 화력 발전의 경제성 평가

—동일 보건 위험도 기준—

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Abstract

On the basis of equal health hazard risk, economic assessment of nuclear was compared with that of coal for the expansion planning of electric power generation in the year 2000. In comparing health risks, the risk of coal was roughly ten times higher than that of nuclear according to various previous risk assessments of energy system. The zero risk condition can never be achievable. Therefore, only excess relative health risk of coal over nuclear was considered as social cost. The social cost of health risk was estimated by calculation of mortality and morbidity costs. Mortality cost was \$250,000 and morbidity cost was \$90,000 in the year 2000.(1986US\$) Through Cost/Benefit Analysis, the optimal emission standards of coal-fired power generation were predicted. These were obtained at the point of least social cost for power generation. In the year 2000, the optimal emission standard of SOx was analyzed as 165ppm for coal-fired power plants in Korea. From this assessment, economic comparison of nuclear and coal in the year 2000 showed that nuclear would be more economical than coal, whereas uncertainty of future power generation cost of nuclear would be larger than that of coal.

요 약

유연탄 발전과 원자력 발전의 경제성 평가를 균등한 인체 위험도 하에서 서기 2000년의 시점에서 수행하였다. 유연탄 발전과 원자력 발전의 인체에 대한 영향 비교에서, 유연탄의 영향이 원자력에 비해서 10배가량 높은 것을 에너지 시스템의 위험도 평가에 관한 여러 연구 결과들로부터 알 수 있었다. 그런데 위험도가 0인 상태는 존재하지 않으므로, 유연탄 발전과 원자력 발전간의 위험도 차이만을 본 논문의 위험도로 간주했다. 인체 위험도 비용은 사망과 질병의 두 경우로 나누어서, 사망의 경우에는 Human Life Value로 계산하고, 질병의 경우에

는 완치될 때까지의 치료비등 제반 비용으로 계산했다. 이러한 방법에 의한 계산 결과 사망의 비용은 $250,000이 되었고, 질병의 경우는 $90,000이 되었다. (1986 US$) 그리고 비용편익분석을 통해서 유연탄 화력 발전의 최적 규제 기준치를 구했는데, 이 규제치는 최소 사회비용이 발생 되는 지점에서 구해졌다. 서기 2000년의 한국에서의 SOx에 대한 최적 규제치는 165ppm으로 나타났다. 이러한 전력 생산의 경제성 평가 방법으로 부터, 원자력이 유연탄 화력에 비해서 더 경제적인 것으로 나타났다. 반면에 불확실도는 유연탄화력이 더 작은 것으로 나타났다.

Nomenclature

A : Weight content of ash in coal(%)
AEx : Average expectancy of life(years)
C : Weight content of fixed carbon in coal(%)
C : Initial letter C in variable name means "coal"
CN : Construction forecost($/kW)
CR : On-site consumption rate of electricity(%)
DC : Discount rate(%)
e : Excess air in fraction
ESP : Electrostatic precipitator
f" : Fraction of ash which leaves boiler
f : Fraction of sulfur leaving boiler after combustion
FER : Fuel price escalation rate(%)
FGD : Flue gas desulphurization
FP : Fuel price
H : Weight content of hydrogen in coal(%)
HR : Heat Rate (kcal/kWh)
IDC : Interest rate during construction(%)
LIFE : Lifetime of power plant(year)
LT : Power plant construction Lead Time(month)
N : Initial letter N in variable name means "Nuclear"
N : Weight content of nitrogen in coal(%)
NOx : Nitrogen Oxides
O : Weight content of oxygen in coal(%)
S : Weight content of sulfur in coal(%)
SICF : Indirect cost factor for FGD
SOx : Sulphur Oxides
TICF : Indirect cost factor for ESP
TSP : Total suspended particulates
VOER : Variable O&M cost escalation rate(%)
VOP : Variable O&M price
WDL : Working day lost
WICF : Indirect cost factor for waste disposal system
XMORB : Morbidity by power generation(deaths/year)
XMORT : Mortality by power generation(diseases or injuries/year)

I. INTRODUCTION

In electric power capacity expansion planning to meet growing power demand, the most important objective has been to minimize the electric power system cost. But as living conditions improved, the public become more concerned with risks to environment and human health. Therefore, risk should be also considered as another important factor in future expansion planning for electric power generation system. Risk can be defined to a hazard or danger with adverse probabilistic consequences to man or to his environment. For the next century, due to economic reasons and limited energy resources, the realistic viable options for electric power generation will be either nuclear or coal-fired power generation system. Many researches have been done to improve methodology of relative economic analysis or risk assessment for coal-fired and nuclear power generation, But up to now, these economic and risk analyses were made separately, and comparisons have not been made at common basis. Therefore, the attempt is made to consider both the relative risk and economic assessment. Health hazards or environment impacts of the two power generation options are different. Also, quantification of risk itself is a difficult problem, and there exist many uncertainties. However, it is possible to quantify partially health hazard of public and occupational workers from construction to decommissioning including fuel cycle based on actual results and previous research works.

In a risk assessment, there are three stage of works ; identification, estimation and evaluation for risk as health hazard. Risk identification means recognizing the existance of hazard and trying to define its characteristics. Risk estimation is scientific determination of risks, usually in as quantitative a way as possible. These include the magnitude, spatial scale, duration and intensity of adverse consequences and their associated probabilities as well as a description of the cause and effect links. Risk evaluation is central to policy determination. Evaluation techniques seek to compare risks with another, and with benefits, as well as providing ways in which the social acceptability combines both to be judged.[1]

Completing these three stage works for health hazard risk, quantified health hazard risk can be turned into social cost, and be used as input data for levelized discounted power generation cost. Then finally, economic assessment outputs including risks are obtained.

However, the quantification of health hazard risk has many uncertainties. Therefore, the data for health hazard risk are set as probability density functions. Then, uncertainty can be represented by probability distribution.

Uncertainty analysis is made to check uncertainty propagation due to uncertain future circumstances. Multivariative uncertainty analysis shows uncertainty of power generation costs due to the coincidence of input uncertainties.

In the past, the social costs have not been fully reflected in the price. Particularly, environmental degradation was almost ignored. In this paper, instead of evaluating the environmental risk, the social cost of electricity generation including the converted environmental risk cost is analyzed. As a scope of this analysis, the economic and public health costs from construction to decommissioning are considered since health risk has an overwhelming importance compared with environmental risk.

II. Quantification of Risk

II-1. Status of regulations for air pollutants

In 1979, in order to protect human health and environmental damage from air pollutants, UN World Health Organization (WHO) proposed the guide values of air quality as a long term target for human health and environmental protection. For SOx, the value is 0.014−0.021ppm and for TSP, it is 0.04−0.06mg/ m^3 . Each country established its air quality standards and emission standards as shown in Table I. For air quality, averaging time is in parenthesis.[2], [3]

In Korea, air quality standards for SOx and TSP are 0.05ppm and 0.150mg/m^3, respectively. During 1980 to 1983, several cities including metropolitan Seoul area had much higher concentration than the air quality standards, although much effort such as using low sulphur oil and coal had been made in order to meet the air quality standards.

Korea must recognize that the emission regulations are loose in comparison with the environmental quality standards of OECD countries. In future, Korean environmental quality standards should be more stringent than present ones.

Table I. National Ambient Air Quality and Emission Standards for Electricity Generating Plants[7]

Nation	SOx(ppm)		TSP(mg/m^3)	
	Quality	Emission	Quality	Emission
F.R.G	0.06(1d)	140	0.48(0.5h)	50
U.S.A	0.028(1y)	215	0.075(1y)	31
Sweden	0.05(30d)	84	0.1(1y)	36
Japan	0.04(1d)	190	0.1(1d)	100
Netherland	0.03–0.1(1d)	192		48
Canada	0.01–0.02	245	0.06–0.07	116
Belgium	0.06(1y)	700		350
Korea	0.05(1y)	1800	0.15(1y)	400
WHO	0.014–0.021		0.04–0.06	
EC	0.028–0.042		0.08	

II-2. Factors to be taken into account

i) Regulations :

Risks depend, of course, on the quality and reliability of facilities. These in turn depend heavily on protection and safety regulations, which vary from country to country.

Regulations determine the "degree of acceptable risks". These standards, however, do not exist everywhere and even though they exist, differ from one country to another. Thus, even where products and technology are identical, the risk may vary depending on the regulations and how strictitly they are enforced.

ii) Choice of sites for establishing production units :

Natural and human environment such as population etc., seriousness of the effects of atmospheric pollutants

iii) The others

—Site selection : This is not only a geographical problem but also a biological problem because radioisotopes present in gaseous effluents and chemical atmospheric pollutants.

—The time factor:

a) techniques, regulations, measurement methods and their accuracy are improved very rapidly, b) progress is also being made in medical and biological knowledge, and in safety and prevention.

II-3. Concepts for consideration of health hazard risk

The concepts for explicit consideration of risk have been developed as follows ;

1) Zero Risk
2) As low as reasonably achievable(ALARA)
3) Best available control technology(BACT)
4) RISK/COST/BENEFIT Analysis :

III. Risk Assessment

III-1. Method

Risk Assessment is the process of assessing the numerical values of the probabilities and the consequences of risks.[7]

Since the environmental implication are associated with different energy options, the ideal assessment has to be the one in which these implications are presented in comparable form to energy options. In other word, the ideal comparative assessment should satisfy the following main conditions :

a) Amenability to economic comparison
b) Quantification of basic parameters
c) Similarity of boundaries
d) Treatment of Uncertainties
e) Consistency of units of comparison.

Typical method for comparing the health effects of different electric energy sources is the fuel-cycle approach standardized to a unit production rate, e.g, 1000-MW(e) power plant-year. The Health-Damage function uses links annual average sulfate exposure to increased annual mortality rate.

Under steady-state conditions, the deaths occurring over future years attributable to pollution exposure this year are equal to the deaths occurring this year, due to the summated pollution exposure of all previous years. Based on this partly, a linear Health-Damage Function is drawn from cross-sectional studies as a simplified way to estimate effects of alternative energy strategies. [8]

III-2. Public and occupational risk assessments

Since comprehensive models of the atmospheric dispersion and conversion of air pollutants in Korea under development are not readily available for the present analysis, rough estimates of public health effects for SO_2 emission are derived from results elaborated for the USA by Brookhaven National Laboratory. (BNL) To estimate damage of long range pollution, BNL used sulfate concentrations as an index of air pollution mix of sulfur-particulate. Its use in this manner is controversial, but it probably remains the best available indicator of health risk.

In BNL analyses for the health effects of air pollution from coal-fired power plants, it was assumed that there existed 3million persons within a 50-miles radius, a sulfur oxide emission rate was 0.41 lb SO_2 per 10 Btu input.

These results are extrapolated linearly to the average local population density and total population of Korea and to the specific emission regulation of coal-fired power generation system. Then, in Korea, health effects of air pollution from coal-fired power plants are much higher than those in BNL analysis. [9] Occupational health risk means the total health risk experienced by all energy production-related workers including fuel cycle range.

Mortalities and mobidities should not be aggregated because it is im possible to determine valid trade-off between them objectively.

III-3. Quantitative estimation of health risk

The following is a summary of the direct comparison of nuclear and coal fuel cycle(assuming currently mandated environmental controls). Attention is given to public and occupational impacts, including accidents and diseases. Effects are normalized to a GW(e)-year basis.

i) Hamilton's data [9]

Table II. Summary of US Health Impacts from Coal and Nuclear Fuel Cycles

Coal		Fuel Cycle		
Morb.	Mort.		Morb.	Mort.
208	1.96–3.13	Extraction	17.84	0.73
3–5	0.014–0.116	Processing	1.653	0.069
40.98	2.035–6.802	Transport	0.101	0.0119
5–390(82)	0.09–77.2(15)	Generation	1.49	0.263
Not Tabulated	Not tabulated	Waste Management	0.0754	0.00627
256.98–643.98(335)	4.139–87.25(22.07)	Summation	21.16	1.08

ii) European perspective on Risk. [11]

Table III. Risk Estimates without Consideration of Storage and Back-up Systems

	Occupational Risk		Public Risk	
	Fatalities (cases)	Injuries/diseases (WDL)	Fatalities (cases)	Injuries/Diseases (cases)
coal	4.0	19,200	0.2–23.2	5.8–90
Nuclear	0.4–1.0	1830–1910	0.2–0.9	0.4–2.7

Integrating above data, health effect of coal-fired power generation is larger than that of nuclear nearly by one order of magnitude. Condition of zero risk is not possible, so the health risk of nuclear is chosen as the base risk. Then, the excess health risk of coal-fired over nuclear is obtained. For health hazard in Korea, Hamilton's data are used as standard and others are used as references. In this case, health risk of fuel mining and processing is not included, because all the fuels are imported. From comparion excess mortalities of coal-fired power generation over nuclear are 1.31–58.59(14) deaths/GW-yr with 70% capacity factor, and excess morbidities are 32.9–302.4(86.8) cases/GW-yr. The values in parenthesis are standard values when input data are assumed to be triangular probabilistic density functions.

Table IV. Synthesis of Health Effects of Power Generation Systems [12]

Health Effects	Nuclear	Coal-fired
Occupational Mortalities	0.01–0.1	0.01–0.03
Occupational Morbidities	1.3	0.9–5
Public Mortalities	0.01–0.16	0.05–150
Public Morbidities	0.–0.03	750–162,000

The above results are obtained when emission standards are 215ppm for SOx and 31 μg/Nm^3 for TSP as the same in the USA now. Therefore, health effects in Korea can be inferred by means of Korean emission standards and assumption of linearity.

III-4. The health risk cost

Costing of mortality and morbidity which result from bronchitis, lung cancer, other cancers, cardiovascular diseases, other diseases of respiratory system by air pollution is based on loss of production, cost of curative care and welfare losses due to death as much as consumption from earned incomes. The case study in the following is connected with health effects of pollution which could be relatively easy to trace and to evaluate.

III-4-1. Mortality cost

Excess mortality cost in monetary value is coincident in Human Life Value(HLV) in monetary value. The HLV can be calculated as following. The cost of excess mortality based on loss of production and welfare losses due to death will be as much as losses from the expected would-be-survivor's earned incomes. So, HLV is approximately equal to the product of Average Expectation of Life(AEx) by per capita Gross National Product(pcGNP).

$$\mathrm{HLV} = (\mathrm{AEx}) \times (\mathrm{pcGNP}) \cdots\cdots\cdots\cdots (1)$$

A) Average Expectation of Life(AFx)

Average Expectation of Life is represented as follow

$$AEx = \sum_{i=1}^{n} \frac{(R_i \times MEx_i \times mR_i) + (100 \times FEx_i \times fR_i)}{(R_i + 100)} \qquad (2)$$

Where i : class of age

R_i : Sex ratio of i

MEx_i : AEx of male, of i

FEx_i : AEx of female, of i

mR_i : Population composition ratio of male, of i

fR_i : Population composition ratio of female, of i

Jsing Table V[18], AEx can be estimated.

$$AEx = 45.53 \ years \ (in \ Korea, 1985)$$

By means of Commissioners standard ordinary mortality Table [19] in USA, calculation of expectation of life in each age is as follow.

$$E_i = \sum_{n=1}^{i} [(n+0.5) \times (\prod_{j=1}^{n} P_{(i-j+1)}) \times (1 - P_{(i-n)})] + [0.5 \times (1 - P_{(i)})] \qquad (3)$$

Where i=99-x(x : age)

E=Expectation of life

P(x)=Probability of living in age x

The calculated results are shown in figure 1.

Table V. Expectation of Life

i	x (Age)	Male		Female		Ri
		MEx$_i$ (year)	mRi (%)	FEx$_i$ (year)	fRi (%)	
1	0–4	64	9.44	70	8.77	108.1
2	5–9	60	10.02	68	9.45	106.5
3	10–14	56	11.46	63	10.76	106.9
4	15–19	51	11.03	59	10.27	107.9
5	20–24	46	10.74	54	10.12	106.6
6	25–29	42	9.94	49	10.13	98.5
7	30–34	37	7.88	44	7.57	104.5
8	35–39	33	6.51	40	6.20	105.4
9	40–44	28	5.49	35	5.44	101.4
10	45–49	24	5.25	31	5.19	101.6
11	50–54	20	4.01	26	4.40	91.6
12	55–59	16	2.79	22	3.48	80.7
13	60–64	13	2.22	18	2.82	79.0
14	65–69	10	1.50	14	2.04	73.7
15	70–74	8	0.96	11	1.52	63.4
16	75–79	6	0.51	8	1.03	49.9
17	80–99	5	0.24	6	0.79	31.1
			100.00			100.0

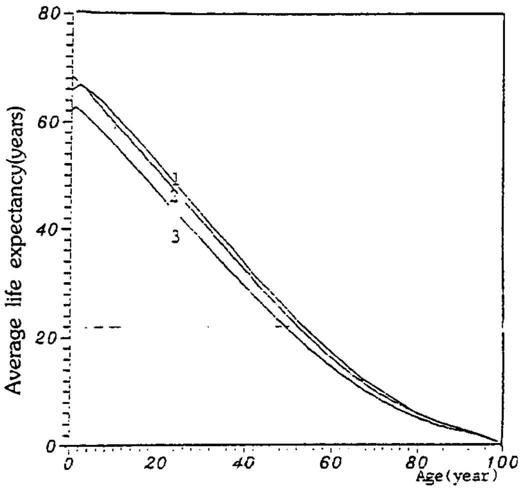

Fig. 1 Average Life Expectancy at Each Age

1 : Average life expectancy in Korea(1985)

2 : Average life expectancy in USA(1958)

3 : Average life expectancy in USA(1941)

From the developed countries expectation of life [10], that of Korea can be estimated to the year 2000. The decrease of infant death rate is taken into account, but other changes are neglected. If infant mortality in calculation of expectation of life can be extrapolated, equilibrium state of average expectation of life can be estimated. The predicted average expectation of life in the year 2000 is roughly 45.6 years.

B) per capita GNP prediction of Korea in the year 2000

Per capita GNP growth rate(Rs) calculation is as follow

$$Rs=[\frac{1+Rg}{1+Rp}]-1 \tag{4}$$

where Rp : population growth rate

Rg=Gross National Product(GNP) growth rate

$$Rp=[\prod_{i=N_1}^{N_2}(1+Rp(i))]-1 \tag{5}$$

$$Rg=\frac{GNP(N_2)-GNP(N_1)}{GNP(N_1)} \tag{6}$$

where N : reference year

$Rp(i)$: population growth rate of i's year

$$\bar{R}_s=\frac{R_s}{N_2-N_1} \tag{7}$$

(Rs : each year average pc GNP growth rate)

Based on GNP from 1962 to 1986 of Korea [15], year 2000's per capita GNP can be predicted by extrapolation. The calculations and predictions are as shown in table VI.

In 1986, Korean Per Capita GNP was 2296(in constant 1986 US $). Per capita GNP in 2000 is predicted as follow in 1986 constant U.S. $.

$$pc\ GNP(2000)=2296\times(1.0776)^{(1990-1986)}\times(1.06)^{(2000-1990)}\approx 5544\text{ US\$} \tag{8}$$

From eqn. (1) and above data obtained, human life value is

$$\text{HLV}=(45.6\text{years})\times(5544\text{US\$/year})\approx 253{,}000\text{ US\$} \tag{9}$$

Table VI. Korean Per Capita GNP Prediction in the Year 2000

Term	1962–69	70–79	80–86	Predicted	
				1987–1990	1990–2000
per capita GNP Average Growth Rate	8.2%	10.02%	7.76%	7.76%	6%

Korean Developnent Institute(KDI) estimated per capita GNP prospect in 2000 at $5433. Based on this value, HLV is approximately $247,000.

So, Human life value can be estimated roughly $250,000 in the year 2000 in Korea.

III-4-2. Morbidity cost

The morbidity cost is obtained from Cohen's result. Cohen calculated cost per fatality averted(1975US$) by various societal activities. morbidity cost is average medical screening and care cost per fatality averted among Cohen's list [16]. The kinds of disease due to air pollution are presented in Table VIII.

Table VII. Cost per Fatality Averted from Medical Screening and Care

Item	Dollars per Fatality Averted
Medical Screening and care	(1975US$)
Cervical cancer	25,000
Breast cancer	80,000
Lung cancer	70,000
Colorectal cancer :	
Fecal blood tests	10,000
Proctoscopy	30,000
Multiple screening	26,000
Hypertension control	75,000
Kidney dialysis	200,000
Mobile intensive care units	30,000

Table VIII. The Kind of Diseases by Air Pollution [17]

Air Pollutants	
Suspended particulates($\mu g/m^3$)	118.14
Arithmetic mean (annual)	
Total sulfates($\mu g/m^3$)	99.65
Arithmetic mean(annual)	
Diseases(per 10,000)	
Tuberculosis of respiratory system	0.53
Malignant neoplasms, including neoplasms of lymphatic and hemopoietic tissues	14.34
Malignant neoplasm of buccal cavity and pharynx	0.34
Malignant neoplasm of digestive organs and peritoneum, not specified as secondary	4.72
Malignant neoplasm of respiratory system, not specified as secondary	2.22
malignant neoplasm of breast	1.26
Asthma	0.29
Diseases of cardiovascular system	48.25
Diseases of cardiovascular system	48.25
Diseases of heart	34.93
Nonrheumatic chronic endocarditis and other myocardial degeneration	2.80
Hypertensive heart diseases	3.53
Influenza	0.34
Pheumonia, except of newbom	3.13
Bronchitis	0.23
Sum of diseases	106.91

On the basis of these tables, average morbidity cost is estimated as follow. Diseases of heart related system form 74.16%. It is assumed that hypertension represents heart diseases. Similarly, lung cancer represents diseases of respiratory system, it forms 2.38%, breast cancer represents breast diseases, and it forms 1.08%.

The other diseases by air pollution are assumed to be cared by mobile intensive care units.

$$\begin{aligned}&\text{Average Morbidity Cost}\\&=(0.7416\times 75{,}000)+(0.0238\times 70{,}000)\\&+(0.0108\times 80{,}000)+(0.2238\times 30{,}000)\\&=\$64{,}816(1975\text{US\$}) \qquad (10)\end{aligned}$$

Therefore, average morbidity cost is roughly $90,000(1986US$)

III-5. Cost-Benefit Analysis

III-5-1. Economic Strategy for Pollutant Emission Control

Since pollution is, to a large extent, and economic problem as well as a technical problem, one possible solution to pollution control can be derived via economic means.

Economic incentives will drive the emitters to operate at the most cost-effective or pareto-optimal point.

The various means suggested are laying tax on emission and the command-counter-proposal-control approach. The latter is a relatively new approach examined by EPA(Environmental Pollution Authority). The subtactics include offset trading, the bubble concept, and banking regulation, and emission reduction credits.

The new approach has the merits of flexibility and cost effectiveness. It is self-propelled by economic incentive, and has good potential for further development.

III-5-2. Pollution Control Cost

In order to calculate the environmental control cost related with various control options to meet the regulation, mass balance equation is used.

The mass balance equations are as follows;

$$\begin{aligned}\text{Flue}=0.05(1+e)\ (f^{0\cdot}S/32+C/12\\+H/4-O/32)+H/400\\+O'3200\ [\text{kmole/kg of coal}] \qquad (11)\end{aligned}$$

$$SOx=(10^6/32)f^{\circ}S/Flue[ppm] \qquad (12)$$

$$TSP=(10^4)f''A/(Flue\times 22.4)\ [mg/m^3] \qquad (13)$$

Calculations of direct and variable costs were developed for currently available air pollution control technologies by J.C. Molburg.[18] The governing equations from Molburg are modified by using US consumer price index[19] *in order to* convert 1986 US$.

IV. Resulte and Diecussion

IV-1. Input Variables for the Generation Cost

In calculation of power generating cost. 28 input variables are required as shown in Table XIII. Some inputs are required to calculate generation cost, and others are required for the pollution control cost and health risk cost. IDC, VOER, DC are common variables to both nuclear and coal. And other technical parameters such as construction cost, capacity factor, lead times, fuel escalation rate, etc. are assumed to vary in a linearly independent manner, and are differently applied to nuclear and coal. Several variables such as nuclear heat rate, coal power plant construction lead time, ash content and three indirect cost factors for FGD, ESP and waste disposal system are assumed constant, because these variables have little effect on total power generation cost. Other variables are assumed to have triangular distributions with the apex of nominal value within the range. Especially, the assumption of triangular distribution in health risk is due to the large uncertainty of its input variables.

IV-2. Cost/Benefit Analysis

IV-2-1. Health Risk Cost

In this paper, health hazard risk is calculated by subtracting nuclear health risk from coal-fired health risk. Because zero risk condition does not exist, nuclear health hazard risk is set as the base reference risk.

When the emission standards in USA(for SOx, 215ppm, for TSP 31 $\mu g/m^3$) is applied, the calculated health risk cost and pollution control cost are as follows;

Table IX. Health Risk Cost and Pollution Control Cost in USA Emission Standard

Emission Standard	Range Division	Health Cost	Control Cost
SOx : 215ppm	Lower	0.547	4.534
TSP: 31 $\mu g/m^3$	Median	2.046	7.466
	Upper	3.351	10.738
	Mean	2.145	7.493

(cost unit : mills/kWh)

These results including uncertainty under USA emission standards are shown in figure 5.6. From the calculated results, assuming linearity, the health risk cost from 1 ppm SOx release is approximately 0.01 mills/kWh, and is approximately equal to the life value of 0.25 deaths. From a reference[20], one man-rem would give roughly 0.00025deaths, and cost-effectiveness criterion was calculated by AIF data and WASH-1400, which was $100 per man-rem, and $1000 per man-rem, respectively. From these values, upper bound of life value is $400,000 and $4,000,000 respectively. And if linearity of radiation exposure effects, at 0.25 deaths, is assumed, $100,000 and $1,000,000 are obtained as cost-effectiveness criterion. These values are compared to the health risk cost calculated here. AIF's criterion is roughly similar to our assumption of life value(250,000US$/death). From this result, we can say that WASH-1400's cost-effectiveness criterion is extraordinary. Health risk cost for keeping the SOx emission standard is shown in figure 5.

IV-2-2. Cost/Benefit Analysis

SOx emission standard, pollution control cost, health risk cost and total generation cost of coal are presented in table XII and figure 4. From these, the optimal(least) social cost for coal-fired power generation is found in the range of 150~170ppm, preferably at 165ppm. This value is much lower than current Korean emission standard(1800ppm). However, summing up only the health risk cost and pollution control cost, at this time, the least cost is found at 125ppm of SOx emission standard. This difference is due to on-site consumption rate of electricity for pollution control.

Therefore, in terms of cost/benefit analysis, the more stringent emission standard is required in Korea by the year 2000.

IV-3. Generation Cost

The power generation costs are calculated at SOx 215ppm, and 165ppm, which are the present emission standards of the USA and estimated optimal regulation in Korea in the year 2000, respectively. Under these regulations, nuclear and coal-fired power generation costs are compared. There are two types in coal-fired power generation cost calculation, depending on whether pollution control and health hazard risk costs are excluded or included in generation cost. The calculated results are shown in figures 6, and tables X, XI with the 90% confidence intervals. The density function width, namely the standard deviation of nuclear power generation cost is wider than that of coal. When the triangular/point distribution is applied, the standard deviation of the coal power generation cost excluding health and control cost is relatively stable in comparison with that of generation cost including pollution control and health risk cost.

Table X. Generation Cost for USA Emission Standards(SOx 215ppm, TSP $31\mu g/m^3$)

	NG	CG	CGn	CGn/NG	CG/NG
90% Confidence Interval	32.573~47.663	44.713~56.318	34.807~44.536	0.823~1.176	1.053~1.490
Mean	40.149	50.125	39.284	0.995	1.269
Standard Deviation	5.988	4.688	3.772	0.140	0.179

(unit : mills/kWh) (1986 US$)

Table XI. Generation Cost for 2000's Emission Standards(SOx 165ppm, TSP $24\mu g/m^3$)

	NG	CG	CGn	CGn/NG	CG/NG
90% Confidence Interval	32.573~47.663	43.307~56.265	34.807~44.536	0.823~1.176	1.046~1.488
Mean	40.149	50.078	39.284	0.995	1.267
Standard Deviation	5.988	4.697	3.772	0.140	0.170

(unit : mills/kWh) (1986 US$)

Notes : NG–Nuclear Power Generation Cost
CG–Coal-Fired Power Generation Cost
(Including pollution control and health risk cost)
CGn–Coal-Fired Power Generation Cost
(Excluding pollution control and health risk cost)

IV-4. Future Optimal Regulation of SOx

The health risk cost based on the life value was calculated. If the life expectancy were calculated by assuming equilibrium state, the health risk cost would be proportional to GNP. So, future regulation will be related to the economic scale of the target year, especially per capita GNP. Assuming 3% real growth rate of per capita GNP in Korea after the year 2000, the optimal regulation level is obtained at 70ppm SOx emission standard in the year 2000, 35ppm for the year 2030. And in the year 1988, optimal level is obtained at 305ppm. Therefore, future optimal SOx emission standard will be as shown in the following table.

Table XII. Future Optimal SOx Emission Standard in Korea

year	1988	2000	2015	2030
optimal SOx regulation	305ppm	165ppm	70ppm	35ppm

Table XIII. Input Data File for the Year 2000

No	Name	Nominal	Range	Probability Distribution	Unit
1	NLIFE	25	20–45	Triangular	year
2	NHR	2500	2500	Point	kcal/kWh
3	NCF	0.7	0.55–0.85	Triangular	decimal
4	NCN	1090	1006–1700	Triangular	Dollar/kW
5	IDC	10	4–13	Triangular	%
6	NLT	70	60–90	Triangular	month
7	NFER	1	0–2	Triangular	%
8	VOER	1	0–2	Triangular	%
9	DC	10	4–13	Triangular	%
10	NFP	3.05	2.84–3.23	Triangular	mills/1000kcal
11	NVOP	5.31	4.25–6.37	Triangular	mills/kWh
12	NCR	6	4–8	Triangular	%
13	CLIFE	2.5	20–40	Triangular	year
14	CHR	2205	2150–2450	Triangular	kcal/kW
15	CCF	0.7	0.55–0.85	Triangular	decimal
16	CCN	508	434–1000	Triangular	Dollar/kW
17	CLT	46	46	Point	month
18	CFER	1	0–2	Triangular	%
19	CFP	8.58	8.0–9.2	Triangular	mills/1000kcal
20	CVOPC	4.33	3.46–5.20	Triangular	mills/kWh
21	CCR	9	7–11	Triangular	%
22	S	2.0	2.0	point	%
23	A	15.7	15.7	point	%
24	SICF	0.8	0.8	point	decimal
25	TICF	0.5	0.5	point	decimal
26	WICF	0.5	0.5	point	decimal
27	XMORT	14.	1.31–58.59	Triangular	deaths
28	XMORB	86.8	32.9–302.4	Triangular	diseases

Table XIV. Coal-Fired Power Generation Cost in Regard to Each SOx Emission Standard

SOx Regulation	Coal-Fired Generation Cost	Pollution control Cost	Health Risk Cost	Health + Control Cost
(ppm)	(mills/kWh)			
20	50.80	9.76	0.202	9.962
50	50.40	9.116	0.501	9.617
100	50.167	8.447	0.999	9.446
120	50.117	8.229	1.198	9.427
125	50.107	8.178	1.248	9.426
135	50.091	8.080	1.350	9.430
150	50.081	7.951	1.497	9.448
160	50.079	7.870	1.597	9.467
165	50.078	7.843	1.630	9.473
170	50.083	7.796	1.697	9.493
190	50.104	7.660	1.890	9.550
215	50.125	7.493	2.145	9.638
230	50.143	7.397	2.295	9.692
270	50.193	7.139	2.693	9.832
300	50.238	6.949	2.992	9.941
325	50.281	6.792	3.242	10.034
1800	61.22	0.	21.397	21.397

(note : We assumed that TSP emission standard is 31 $\mu g/m^3$ at SOx 215ppm, and TSP standard is in proportion to SOx emission standard)

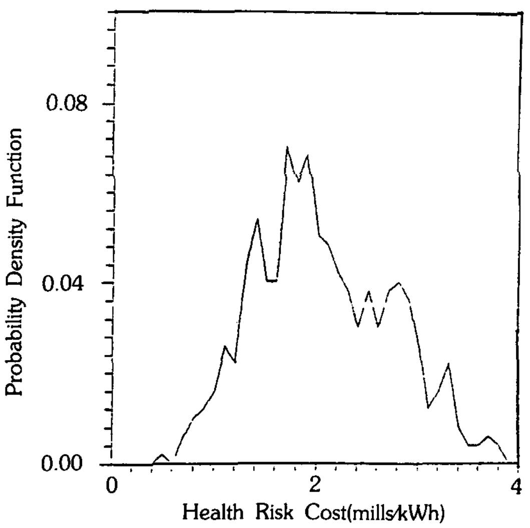

Fig. 2 Probability Distribution of Levelized Discounted Health Risk Cost for Coal-fired Power Plant for Emission Standard of SOx 215ppm

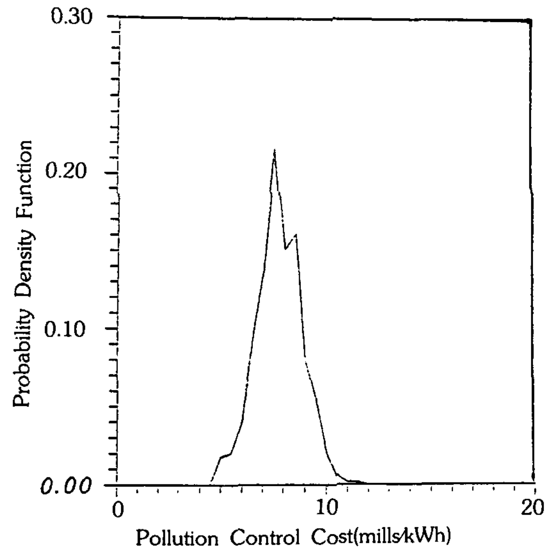

Fig.3. Probability Distribution of Levelized Discounted Pollution Control Cost for Coal-fired Power Plant in Emission Standard of SOx 215ppm

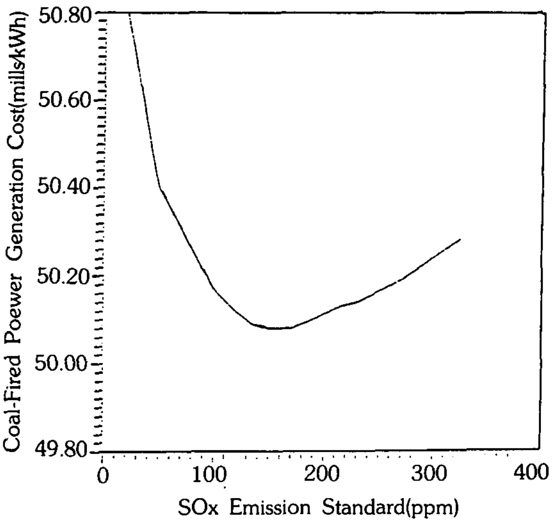

Fig. 4 Graph of Levelized Discounted Power Generation cost for Coal-fired Power Plant with eath SOx Emission Standard

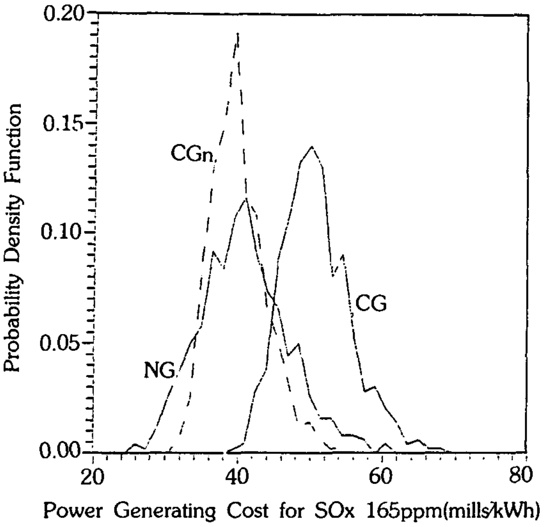

Fig. 6 Relative Probability Distributions of Levelized Discounted Power Generation Costs for Nuclear and Coal-fired Power Plants

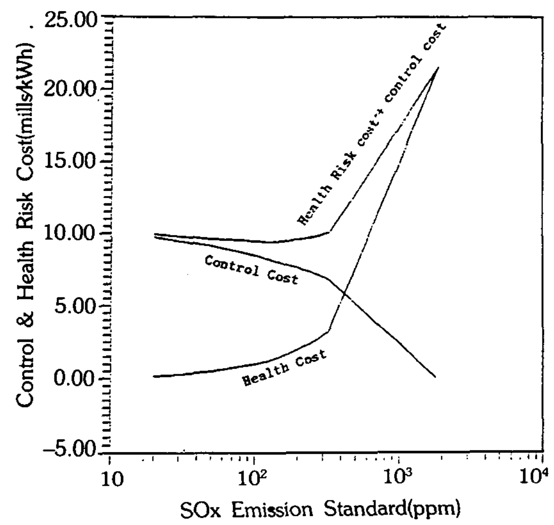

Fig. 5 Graph of Levelized Discounted Health Risk Cost and Control Cost for Coal-fired Power Plant

V. Conclusion

The conclusions from this study are as follows.

1. The excess mortalities of coal-fired power generation compared with nuclear are 1.31~58.59 deaths/GW-yr and excess morbidities are 32.9~302.4 cases/GW-yr at 70% capacity factor for US emission standards. The analysis based on equal health hazard risk will be useful in the future electric expansion planning in Korea in order to incorporate social cost.

2. The health risk cost is obtained by summing the mortality and morbidity cost. Mortality cost is estimated by human life value and morbidity cost by cost per fatality averted from medical screening and care. Life value is approximately equal to the product of average life expectancy by per capita GNP. Average life expectancy is 45.6years and per capita GNP is $5544(1986US$) in the year 2000 in Korea. So, mortality cost is approximately $250,000 per death, and morbidity cost is $90,000 per case. The excess health risk cost of coal-fired power generation under US emission standards of SOx 215ppm, TSP 31 $\mu g/m^3$ is approsimately 2.15mills/kWh in Korea.

3. Future regulatory standard should be decided by cost/benefit analysis. The optimal regulation levels of SOx are obtained at 305ppm in 1988,

165ppm in 2000, 70ppm in 2015, and 35ppm in 2030.

4. Under equal health hazard risk basis, economic comparison of nuclear and coal in the year 2000 turns out that nuclear is far more economic than coal. At the emission level of SOx 165ppm, levelized discounted nuclear power generation cost was 40.149mills/kWh and that of coal was 50.078mills/kWh. So, the power generation cost differential expected to be approximately 10mills/kWh in the year 2000 in Korea.

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