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# Power Generation Cost Comparison of Nuclear and Coal Power Plants in Year 2001 under Future Korean Environmental Regulations

## – Sensitivity and Uncertainty Analysis –

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# 미래의 한국의 환경규제여건에 따른 2001년도의 원자력과 석탄화력 발전단가비교

## – 민감도와 불확실도 분석 –

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## Abstract

To analyze the impact of air pollution control on electricity generation cost, a computer program was developed. POGEN calculates levelized discounted power generation cost including additional air pollution control cost for coal power plant. Pollution subprogram calculates total capital and variable costs using governing equations for flue gas control. The costs are used as additional input for levelized discounted power generation cost subprogram. Pollution output for Flue Gas Desulphurization direct cost was verified using published cost data of well experienced industrialized countries. The power generation costs for the year 2001 were estimated by POGEN for three different regulatory scenarios imposed on coal power plant, and by levelized discounted power generation cost subprogram for nuclear power. Because of uncertainty expected in input variables for future plants, sensitivity and uncertainty analysis were made to check the importance and uncertainty propagation of the input variables using Latin Hypercube Sampling and Multiple Least Square method. Most sensitive parameter for levelized discounted power generation cost is discount rate for both nuclear and coal. The control cost for flue gas alone reaches additional 9-11 mills/kWh with standard deviation less than 1.3 mills/kWh. This cost will be nearly 20% of power generation cost and 40% of one GW capacity coal power plant investment cost. With 90% confidence, the generation cost of nuclear power plant will be 32.6-51.9 mills/kWh, and for the coal power plant it will be 45.5-60.5 mills/kWh. Nuclear is favorable with 95% confidence under stringent future regulatory requirement in Korea.

## 요 약

대기 오염의 제어가 발전 단가에 미치는 영향을 분석하기 위하여 전산 모델이 개발 되었다. POGEN은 석탄 화력 발전소에 대해 대기 오염 제어 비용을 가산한 균등화 발전 단가를 계산한다. 부 프로그램 Pollution은 대기 오염 제어 비용을 가산한 지배 방정식을 사용하여 총 자본 비용과 변동비용을 계산한다. 이 비용은 균등화 발전 단가를 계산하는 부 프로그램 GENeration

의 추가 입력으로 사용된다. 탈황설비의 직접 비용에 대한 Pollution을 이용한 결과는 경험이 풍부한 선진국에서 발간된 비용 자료로써 검증하였다. 2001년의 전력 생산 비용은 석탄화력 발전소에 적용된 세 가지의 규제 시나리오에 의해 추정되었다. 입력 변수의 중요도와 미래 발전소에 대한 입력 변수에 포함된 불확실성 때문에 생기는 불확실도의 전파를 검토하기 위해 Latin Hypercube Sampling과 Multiple Least Squares 방법을 사용하여 민감도 분석과 불확실도 분석을 수행하였다. 가장 민감한 입력 변수는 원자력, 화력 공히 할인률이다. 배출가스제어 비용으로써 9-11 mills/kWh 정도가 추가 되어야 한다. 이 비용은 전력 생산 비용의 거의 20 퍼센트가 되고, 이에 해당하는 투자비는 1GW 용량의 석탄 화력 발전소 초기 투자 비용의 40%가 될 것이다. 원자력 발전에 대한 단가는 90퍼센트의 신뢰도로써 32.6-65.9, 석탄 화력에 대해서는 45.5-60.5 mills/kWh가 되며, 엄격한 규제 분위기 하에서는 원자력이 95%의 신뢰도로써 유리할 것이 전망된다.

## Nomenclature

$\tilde{A}$ : Fly ash removal capacity in tons/hr
$AR_{ESP}$ : ESP collector area in $ft^2$
$B_i$ : Regression coefficient of the i´th variable
C : Initial letter C in variable name means "Coal"
CAP : Scrubber reagent capacity in tons/hr
CF : Levelized Capacity Factor
CG : Levelized coal power generation cost (subscript n, 1,2, and 3 mean without control cost and with that of scenario 1,2 and 3)
$CI_C$ : Levelized Investment Cost for Control Equipment (Dollar per year)
CN : Construction Forecost (Dollar/kW)
CR : On-site consumption rate of electricity(%)
$CV_C$ : Levelized Variable Cost for Control Equipment (Dollar per Year)
DC : Discount rate(%)
ESP : Electrostatic precipitator
$f_{bypass}$ : Fraction of flue gas not scrubbed
$F_C$ : Levelized Fuel cost(Dollar per year)
FER : Fuel price escalation rate(%)
FGD : Flue gas desulphurization
FP : Fuel price
$\tilde{G}$ : Flue gas flow rate at full capacity in actual cubic ft per min
$\hat{G}$ : Flue gas flow rate capacity through scrubber in acfm
$G_C$ : Levelized electricity generation cost (mills/kwh)
$G_C'$ : Levlized electricity generation cost including control cost
HR : Heat Rate(kcal/kWh)
$I_C$ : Levelized Investment cost(Dollar per year)
IDC : Interest rate during construction(%)
LC : Waste disposal land cost in a thousand Dollar/acre
Life : Lifetime of power plant
LT : Power plant construction lead time(month)
$MW_g$ : Gross power plant capacity
n : Booklife of alternative(year)
N : Initial letter N in variable name means "Nuclear"
NG : Levelized nuclear power generation cost(mills/kWh)
NOP : Number of operating scrubber trains
$NO_X$ : Nitrogen oxides
NSP : Number of spare scrubber trains
$O_C$ : levelized O&M cost (Dollar per year)
$P_g$ : Levelized gross electricity generation per year(MWh) $=(MW_g \times 8760h \times CF)$
$P_{net}$ : Levelized net electricity generation per year(MWh)
POGEN : Computer code name which calculates electricity generation cost with pollution control
R : Repetition factor flue gas to be scrubbed
RC : Scrubber reagent cost in Dollar/ton
$R^2$ : coefficient of determination
$\tilde{S}$ : Scrubber $SO_2$ removal capacity in tons $SO_2$/hr
Si,y : Standard Deviation of i´th variable or output parametery
SICF : Indirect cost factor for FGD
$SO_X$ : Sulphur oxides
TICF : Indirect cost factor for ESP
TSP : Total Suspended Particulate
VOER : Variable O&M cost escalation rate(%)

VOP : Variable O&M price

WICF : Indirect cost factor for waste disposal system

X : Electricity requirement for FGD/ESP (fraction of net electric power without FGD/ESP)

$\beta_i$ : Standardized regression coefficient of i´th variable

$\eta_{FGD}$ : $SO_X$ removal efficiency of FGD

$\eta_{SOX}$ : $SO_X$ removal efficiency requirement

$\phi$ : levelized fixed charge rate

´ : ´means the costs are estimated in constant money basis.

## 1. Introduction

Due to TMI and Chernobyl nuclear accidents, nuclear power plant had to be subject to more stringent safety requirement. Therefore, nuclear power generation cost has in recent years increased somewhat. However, in future expansion planning for electrical generating system, the realistic viable options would be either nuclear or coal power generating system due to finite energy resources and technoeconomic reasons. For such planning, the new nuclear power plants were introduced in many national electric grid system based on the economic comparability with the existing coal-fired power plant.

Optimizing an electricity generation alternative for next century, various uncertain and qualitative future aspects must be considered together with cost analysis. Increasing attention on the clean environment and clean energy supply requirements have to be taken into account for future electric power system expansion planning as the environmental impacts and control cost of energy systems.

In spite of these international trends, Korean current environmental regulation for air pollutant emission of coal power plant is much weaker than other industrialized countries. Therefore, Korea Advanced Energy Research Institute and Korea Electric Power Corporation estimated more stringent regulation and mandatory inclusion of Flue Gas Desulphurization(FGD) in future.

On the other hand, environmental regulations for Korean nuclear power plant are the same level as the industrialized countries because of recent public concerns of nuclear safety.

In addition, nuclear has a few hundredth or thousandth of health risks than coal even under the current regulatory requirement of industrialized conutries$^{1)}$. Whereas 50% FGD installation has 4 times or more lives saved cost effectiveness in coal power plant than recombiner or 6 charcoal beds added in nuclear power plant$^{2)}$. In this situations, coal power plant would likely be subjected to more environmental control than nuclear in future.

Levelized discounted power generation cost is the most prevailing and reasonable basis for national and international comparisons of investment choices for equivalent services. In order to compare the economics between nuclear and coal power plants to be commissioned commercially in 2001 with stringent environmental regulation, the environmental control cost has to be included in the electricity generation cost. The cost data have to be estimated carefully due to long time horizon and uncertainty in the estimation of the input variables.

Thus, a computer code POGEN was developed. POGEN calculates levelized discounted power generation cost taking into account of an dadditional cost due to environmental polution control(total suspended particulates, sulphur oxides, and treatment of subsequent wastes) to meet the future regulatory requirements. The analysis is based on three scenarios for $SO_X$ and TSP regulation levels.

Environmental capital and variable costs were calculated for TSP control, $SO_X$ control and waste disposal, and these were used as the additional input of levelized discounted power generation cost subprogram.

Sensitivity and uncertainty analysis was made to check the importance of the inputs and uncertainty propagation due to uncertain future circumstances. One variable-at-a-time sensitivity results show the relative importance of inputs, and multivariate uncertainty analysis shows uncertainties of generation costs due to the coincidence of input uncertainties.

## 2. A Quantification of Environmental Impacts

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[3,5] as a long term target for human health and environmental protection. For $SO_X$, the value is 0.014-0.021ppm and for TSP, it is 0.04-0.06 mg/Nm$^3$. European Community adopted "the Directive on Air Quality Limit and Guide Values." According to this quality limit, $SO_X$ concentration in air shall not exceed 0.028-0.042 ppm (80-120㎍/㎥) and TSP shall not exceed 0.08 ㎎/㎥. The guide values are same as WHO. Each country establishes its quality standard and emission standards corresponding to it as shown in Table I. For air quality, averaging time is in parenthesis.

In Korea, air quality standards for $SO_X$ and TSP are 0.05 ppm and 0.150㎎/㎥ respectively. During period from 1980 to 1983, several cities including metropolitan Seoul area had excess concentration than the air quality standards, although much effort to use low suphur oil, etc could meet the air quality standards thereafter.[5] It is generally accepted that in future, Korean enviromental quality standard would have to be more stringent than presently enforced ones. Japan reinforced environmental regulation stringently upward ten times during 60s and 70s[5]. Being different according to specific area, polluted urban area apply 190 ppm $SO_X$ and 100 ㎎/Nm$^3$ TSP for general standard, 70 ppm $SO_X$ and 50 mg/Nm$^3$ TSP for special standard.

Table I. National Ambient Air Quality and Emission Standards for Electricity Generating Plants[4]

| Nation | $SO_X$(㏙) | | TSP(㎎/Nm$^3$) | |
|---|---|---|---|---|
| | 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 |
| Netherlands | 0.03-0.1(1d) | 192 | | 48 |
| Canada | 0.01-0.02(1y) | 245 | 0.06-0.07(1y) | 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 | |

As a guide value for enviromnental regulation in the year of 2000, KAERI study[5] proposed 200-250 ppm for $SO_X$, 200-250 ppm for $NO_X$, 100-150mg/Nm$^3$ for TSP, and their corresponding emission targets in power plant was proposed as 100 ppm for $SO_X$, 100 ppm for $NO_X$ and 50 mg/Nm$_3$ for TSP. The proposed regualtion by KEPCO[6] are 150 ppm, 100 ppm, 50 mg/Nm$^3$ for $SO_X$, $NO_X$, and TSP, respectively.

In this study, emission target value in power plant to be reached in the year of 2001 are proposed as 150 ppm for $SO_X$, 50mg/Nm$^3$ for TSP. For the scenario approaches, the followings are assumed.

(1) Scenarion I is the weakest regulation requirement. Scenario III is the most extreme case and scenario II is medium case.

(2) Per 10 years, the the regulation is reduced to its half value.

The second assumption is based on the past trends in industrialized countries and that for every 10 years the size of environmental polluting sources such as the number of coal power plants increases about twice and this is reasonable. Therefore, the proposed scenarios for regulations are as shown in table II.

## 3. Governing equations and POGEN Description

### 1) Governing Equations and Series Configuration Model

Model of direct and variable costs for currently available air pollution control technologies was developed by J.C.Molburg[7] In this model, a nominal or basic

**Table II : Assumed Target Scenarios for $SO_x$ and TSP Control in Korea**

| $SO_x$(ppm) | now | 1995 | 2001 | 2011 | 2021 |
|---|---|---|---|---|---|
| Scenario I | 1800 | 300 | 150 | 75 | 38 |
| Scenario II | 1800 | 200 | 75 | 38 | 19 |
| Scenario III | 1800 | 100 | 38 | 19 | 10 |
| | | | | | |
| TSP(mg/Nm$^3$) | now | 1995 | 2001 | 2011 | 2021 |
| Scenario I | 400 | 100 | 50 | 25 | 13 |
| Scenario II | 400 | 50 | 25 | 13 | 7 |
| Scenario III | 400 | 30 | 13 | 7 | 4 |

engineering design was first assumed for each technology, and the cost of that design was determined from detailed studies or models reported by other investigators, and then using the multiple regression analysis, the model calculates the costs for components of similar designs as pollutant emission constraints, coal characteristics, component size(or capacity), and economic basis are varied.

In order to calculate $SO_x$ control cost even in case of extremely stringent regulation, series configuration model of scrubber was devised. $SO_x$ removal efficiency of FGD $\eta_{FGD}$) was assumed to be 90%. When $SO_x$ removal efficiency requirement($\eta_{SO_x}$) is less than $SO_x$ removal efficiency of FGD ($\eta_{FGD}$), it needs not scrub full flue gas, and therefore, some portion of flue gas can be bypassed. If a scrubber of 125 MW capacity takes charge of flue gas, the number of operating scrubber trains(NOP) is

$$NOP=(1-f_{bypass})\cdot MW_g/125 \text{ (nearest integer)}$$

where, $MW_g$ is gross power plant capacity in MW and $f_{bypass}$ is $1-\dfrac{\eta_{SO_x}}{\eta_{FGD}\ \eta_{SO_x}}$

But, when $SO_x$ removal efficiency requirement $\eta_{SO_x}$ is greater than $SO_x$ removal efficiency, the flue gas must be scrubbed repetitiously until until the $SO_x$ concentration of flue gas meets the regulation requirement. If the repetition factor R is defined as the number(real number) which flue gas is to be scrubbed, the repetition factor R must meet the equation

$$1-\eta_{SO_x}\geqq(1-\eta_{FCD})^R.$$

Therefore,

$$NOP=\frac{MW_g}{125}\times R\text{(nearest integer)}$$

For estimating equation for other technical parameter, refer to Molburg[7]. The governing equations from Molburg were modified using US consumer price index[8] in order to convert to 1986 US Dollar. Table III shows these equations adopted.

### 2) Mathematical Model for Lifetime Levelized cost of Generation

The constant dollar levelized bus bar cost[9] in mills/kWh can be defined as the sum of the constant dollar levelized annual fixed cost and the constant dollar levelized variable cost divided by the levelized electric generation. Energy Systems Group of Management Science Dept., KAIST developed 4 methods[10] according to the input data assumptions whether the investment cost is generated at a time or not, and whether annual cost data are assumed to be constant or not.

For the future decision analysis, the simple method is used because it is difficult to detect the annual variation of each variables such as electricity generation, capacity factor, annual cost, etc. But in order to detect the effect of interest rate during construction (IDC) and lead time (LT), investment cost enters in the form of forecost and the investment schedule is assumed to be a standardized S curve[9] of investment theory.

### 3) POGEN Description

As shown in Fig.I, POGEN consists of three major parts. First calculating levelized discounted power generation cost, second calculating pollution control

**Table Ⅲ. Direct and Variable Cost of Control Equipments**

| Component/Option | direct Cost |
|---|---|
| Hot-side ESP | $27.03\times10^{6}(AR_{ESP})^{0.97}+7.695(GW_g)$ |
| Limestone FGD system<br>1.Material Handling<br>a) CAP<28.2<br>b) CAP≧28.2 | <br><br>$0.1991(CAP)+3.251$<br>$0.0887(CAP)+6.374$ |
| 2.Scrubber Trains | $(NOP+NSP)\times[3.478+\frac{0.0507\tilde{S}+1.299\times10^{-5}\hat{G}}{NOP}]$ |
| Solid Waste Disposal | $(LC)(0.00784\,\tilde{S}^{1.017}+0.0020\,\tilde{A}^{-0.7})+(2.24+0.865\,\tilde{S}^{0.8}+0.525\,\tilde{A}^{-0.6})$ |
| Component/Option | Variable Cost |
| Hot-side ESP | $14.594\times10^{8}(CF)(AR_{ESP})$ |
| Limestone FGD system<br>1.Material handling<br>2.Scrubber Trains | <br>(included below)<br>$1.1366\times10^{3}\,CF\times$<br>$[9.11(CAP)(RC)+143\,\tilde{S}+0.00356\,\hat{G}+2000]$ |
| Solid Waste Diposal | $0.175(\tilde{S}\times CF)^{0.71}+0.108(\tilde{A}\times CF)^{0.6}+1.449$ |

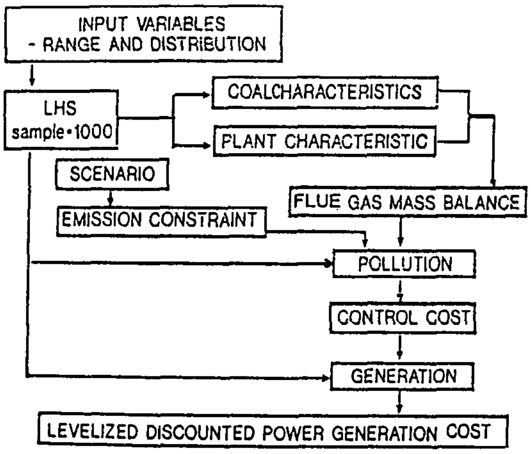


Fig Ⅰ. POGEN Logic Diagram

cost and third Latin Hypercube Sampling (LHS) process. The first and second sub-program requires the input values, LHS sub-program provides three input data sets.

Levelized generation cost, $G_c$ in mills/kWh, is calculated by three terms: Levelized investment cost in dollar/year($I_c$), levelized O&M cost in dollar/year($O_c$), and Levelized fuel cost in dollar/year($F_c$). If power plant generates $P_g$ MWh($P_g=MW_g\times8760h\times$Levelized Capacity Factor) with consumption rate CR, then Gc is,

$$G_c=\frac{F_c+O_c+I_c}{P_{net}}=\frac{F_c+O_c+I_c}{P_g(1-CR)}$$

Each pollution control has two cost term, levelized investment($CI_c$) and O&M($CV_c$) cost in dollar/year, with energy requirement of rate X. These have to be added to generation cost. New generation cost $G_c'$ is, therefore,

$$G_c'=\frac{(I_c+CI_c)+(O_c+CV_c)+F_c}{P_{net}(1-X)}$$

$$=\frac{G_c}{1-X)}+\frac{CI_c}{P_{net}(1-X)}+\frac{CV_c}{P_{net}(1-X)}$$

## 4. Sensitivity and Uncertainty Analysis[11]

The most economic comparison method for future generation cost analysis is based on the assumption that the properly estimated input data will be realized in the future. Probably, the actual future values of the input variables will differ from what is used in the deterministic estimate today. The deterministic method gives no quantitative measure of this uncertainty. However, a probabilistic analysis can quantify the uncertainty by providing a probability distribution of the expected total power generation cost from a given type of power plant. Kent A. Williams et al. have studied the input uncetainty propagation through the generation cost model by use of Monte Carlo driver code[12-13].

### 1) Latin Hypercube Sampling[11]

In studying a mathematical model, the more complex it is, the more important good sampling is. In order to reduce the uncertainty of simulation output, Latin Hypercube Sampling of input variable technique is devised[14]. To obtain a Latin Hypercube sample, above all, stratified samples of size N are obtained on each input variable. Then, the stratified samples of size N on $X_k$ is permuted into a random order to get a input matrix ($X_{ki}$) using randomization method.

### 2) Multiple Least Square and Sensitivity Coefficient[15]

This method is usually used to generate an approximate relationship between the input parameter and the output variable considering the system as a black box. When the output variable y is a complex function of a number of input variables, $X_i(i=1,\cdots,k)$, that is, $y=f(x_1,x_2,\cdots x_k)$, the input-output relationship can be approximated in polynomial as

$$y=Xb+e,$$

where, $y=n\times1$ : observed data vector, $X=n\times m$ : design matrix, $b\times1$ : coefficient vector, $e=n\times1$ : error vector, i.e., the difference between observed data and estimated response, n=number of observations (runs), and m=1+number of variables.

The best-estimated regression coefficients can be found by the method of least squares, sum of squares of the error is minimized when $b=(x^Tx)^{-1}x^Ty$. · Where, superscript T means transpose of a matrix.

The $B_i$, each component of the coefficient vector b, represents the slope of y with respect to $X_i$. But the actual magnitude of the coefficients depends on the units in which the variables are measured. Only if independent variables are measured in the same unit, their coefficients are directly comparable. Therefore, the standardized regression coefficient, $\beta_i$, is the sensitivity parameter in a sense[15].

$$\beta_i=B_i\frac{S_i}{S_y},$$

where $S_i$ and $S_y$ are the standard deviations of the i´th variable and output parameter y. In fact, the $\beta$-coefficient is the slope of the least squares line when both X and Y are expressed as Z scores. The regression coefficient $B_i$ and its standard form, $\beta_i$, are bases for one-variable-at-a-time sensitivity.

### 3) Sensitivity and Uncertainty Analysis Procedure

After the model and simulator POGEN is constructed, the next step of uncertainty and sensitivity analysis is the definition of uncertain inputs. The uncertainties of the inputs can be defined by the range and probability distribution within the range.

For the first stage analysis, all inputs are assumed to be uniform distribution. Then, LHS input sets are selected and levelized discounted power generation costs are calculated by POGEN. The LHS result data set and generation costs are used as the input of the SPSS/PC+ (Advanced PC version of Statistical Package for Social Science) to apply the multiple least square method.

The regression result generates the regression coefficient $B_i$, and its standardized form $\beta_i$. Because the $\beta_i$ is sensitivity parameter, variables of low $\beta$ value (less than 0.05) were neglected as if they are constant at their nominal values. The others are assumed to be triangular distributions in the region with the apex of nominal value. This assumption provides second stage analysis. The new $\beta_i$ and $B_i$ are the bases for single variable sensitivity study.

A thousand of generation cost data go through the sorting procedure. the 40 intervals are used. Sorting the output $Y_i$ and counting within each interval is rammed. At this stage, probabilistic and cumulative parameters are calculated. From this results, the input uncertainties propagation through the model POGEN distribution functions are obtained and other statistics is studied. Fig.II shows this procedure schematically.

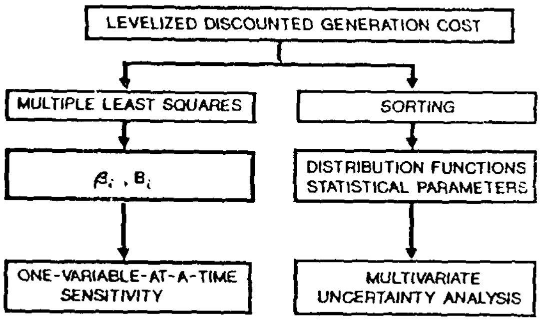


**Fig II. Sensitivity & Uncertanty Analysis Logic Diagram**

## 5. Result and Discussion

### 1) Code Verification

In order to verify pollution subprogram, FGD investment cost predicted by the subprogram is compared with published data as presented in Fig III. The eleven published data points are from Japan and OECD data.

The points A, B, and C are results from A.Kinoshita[6], who studied environmental control cost of coal power plant in-service in 1990, and intended to represent the standardized typical cost estimates based on actual experience and on various studies taking into account of system complexity and diversity, as well as uncertainties concerning future market.

The points D, E, F are Japanese estimate, too. They are case study result[7] based on Takasago, Mathushima and Takehara power plants. The points G to J are from OECD data[8]. FGD investment cost is a strong function of $SO_X$ regulation level and sulphur content of coal. The figure shows that the Pollution subprogram is useful to estimate the FGD investment cost and total $SO_X$ control cost.

### 2) Input Variables for POGEN

In order to run POGEN, twenty six input variables are required as shown in Table IV. Most nominal values of inputs are best estimated values for KEPCO long-term electric generation expansion planning in 1987. For most variables, the ranges are determined in consideration of Korean and foreign experiences.

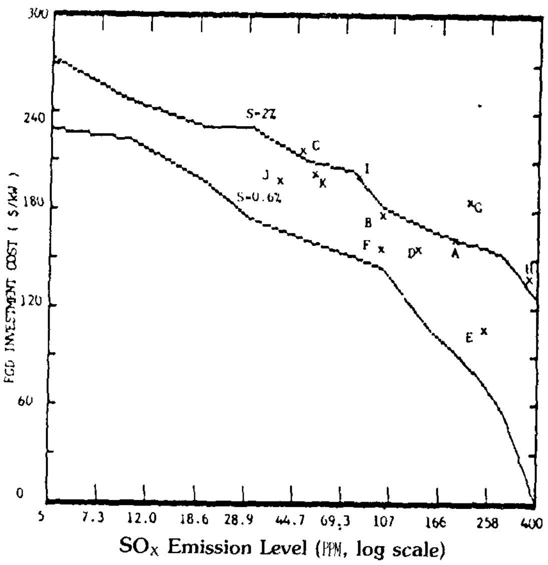


**Fig. III Required FGD Investment Cost for $SO_X$ Regulation Level.**

From the analysis with uniform distribution, several variables are assumed constant because their $\beta$-coefficients are less than 0.05. Other variables are assumed to be triangular distributions with the apex of nominal value within the range. The ranges and the nominal values for inputs are shown in Table IV.

### 3) One-variable-at-a-time sensitivity

The LHS result data and levelized discounted power generation cost of POGEN output were used as input of SPSS/PC+ to get simplified linear model for generation cost and sensitivity parameter, i.e., correlation coefficient of the input variables. The obtained linear models for nuclear electricity generation cost(NG), coal power plant electricity generation cost with regulation scenario I($CG_I$) and coal power plant electricity generation cost without any control equipment($CG_n$) are shown in Table V.

Coefficient of determinations, $R^2$, are 98.0%, 98.0% and 97.8% for NG, $CG_I$,and $CG_n$ respectively. One variable-at-a-time sensitivity is based on the $\beta$-coefficient and the regressed linear model. As

**Table Ⅳ. Input Data File for the Year 2001**

| NO | Name | Nominal | Range | Probability Distribution | Unit |
|---|---|---|---|---|---|
| 1 | NLIFE | 25 | 20-45 | Uniform/Triangular | year |
| 2 | NHR | 2500 | 2457-2606 | Uniform/Point | kal/kWh |
| 3 | NCF | .7 | .55-.85 | Uniform/Triangular | decimal |
| 4 | NCN | 1090 | 1006-1700 | Uniform/Triangular | Dollar/kW |
| 5 | IDC | 10 | 4-13 | Uniform/Triangular | % |
| 6 | NLT | 70 | 60-90 | Uniform/Triangular | month |
| 7 | NFER | 1 | 0-2 | Uniform/Triangular | % |
| 8 | VOER | 1 | 0-2 | Uniform/Triangular | % |
| 9 | DC | 10 | 4-13 | Uniform/Triangular | % |
| 10 | NFP | 3.05 | 2.84-3.23 | Uniform/Triangular | mills/$10^3$kcal |
| 11 | NOVP | 5.31 | 4.25-6.37 | Uniform/Triangular | mills/kWh |
| 12 | NCR | 6 | 4-8 | Uniform/Triangular | % |
| 13 | CLIFE | 25 | 20-40 | Uniform/Triangular | year |
| 14 | CHR | 2205 | 2150-2450 | Uniform/Triangular | kcal/kWh |
| 15 | CCF | 0.7 | 0.55-0.85 | Uniform/Triangular | decimal |
| 16 | CCN | 508 | 434-1000 | Uniform/Triangular | Dollar/kW |
| 17 | CLT | 46 | 40-60 | Uniform/Point | month |
| 18 | CFER | 1 | 0-2 | Uniform/Triangular | % |
| 19 | CFP | 8.58 | 8.0-9.2 | Uniform/Triangular | mills/$10^3$kcal |
| 20 | CVOPC | 4.33 | 3.46-5.20 | Uniform/Triangular | mills/kWh |
| 21 | CCR | 9 | 7-11 | Uniform/Triangular | % |
| 22 | S | 0.6(2.0) | .54 | Uniform/Point | % |
| 23 | A | 15.7 | 10-20 | Uniform/Point | % |
| 24 | SICF | 0.8 | 0.45-1.0 | Uniform/Point | decimal |
| 25 | TICF | 0.5 | 0.45-1.0 | Uniform/Point | decimal |
| 26 | WICF | 0.5 | 0.45-1.0 | Uniform/Point | decimal |

**Talbe Ⅴ. Linear Model for Generation Costs.**

$$\mathrm{NG}=2.176(\mathrm{DC})+0.0206(\mathrm{CN})-37.79(\mathrm{CF})+0.523(\mathrm{IDC})-0.160(\mathrm{LIFE})+0.0956(\mathrm{LT})+1.179(\mathrm{VOP})+0.960(\mathrm{FER})+0.359(\mathrm{CR})+0.611(\mathrm{VOER})+3.00(\mathrm{FP})-3.964$$

$$\mathrm{CG}_{\mathrm{I}}=1.443(\mathrm{DC})+0.0207(\mathrm{CN})+2.29(\mathrm{FER})-28.65(\mathrm{CF})+0.013(\mathrm{HR})+2.814(\mathrm{FP})+0.651(\mathrm{S})+0.598(\mathrm{CR})+1.226(\mathrm{VOP})+0.865(\mathrm{VOER})-0.079(\mathrm{LIFE})+0.140(\mathrm{IDC})-22.446$$

$$\mathrm{CG}_{\mathrm{II}}=0.02(\mathrm{CN})+2.231(\mathrm{FER})+0.938(\mathrm{DC})-18.81(\mathrm{CF})+0.0115(\mathrm{HR})+2.73(\mathrm{FP})+1.184(\mathrm{VOP})-0.478(\mathrm{CR})+0.138(\mathrm{IDC})+0.503(\mathrm{VOER})-0.050(\mathrm{LIFE})-24.725$$

shown in Table Ⅵ. $\beta$-coefficient shows relative importance of each variable, and the minus sign means that the generation cost and the input parameter vary in a opposite manner.

Discount rate (DC) is most sensitive parameter for both coal and nuclear power generation cost. $\beta$ values of DC are 0.697 for NG, and 0.602 for $\mathrm{CG}_{\mathrm{I}}$. Coal generation cost excluding the control cost is most sensitive to the construction forecost(CN).

The important parameters for NG are construction forecost, capacity factor, interest rate during constuction, lifetime and lead time, etc. Those for CG are construction forecast(CN), capacity factor (CF), fuel price escalation rate(FER), heat rate(HR) and fuel price (FP). Consumption rate and sulphur content are important relatively. For unclear power plant, parameters related to thefixed cost are important, whereas for coal power plant those related to the variable cost are relatively important.

The graphical presentation of single-variable sensitivity for DC is shown in Fig.Ⅳ Nuclear power generation cost varies by 2.176 mills/kWh per each 1% discount rate change. Break even point of NG and $\mathrm{CG}_{\mathrm{II}}$ occurs nearly at eleven percent of DC. About 62% for capacity factor and 0.7% for fuel escalation rate are the break even points.

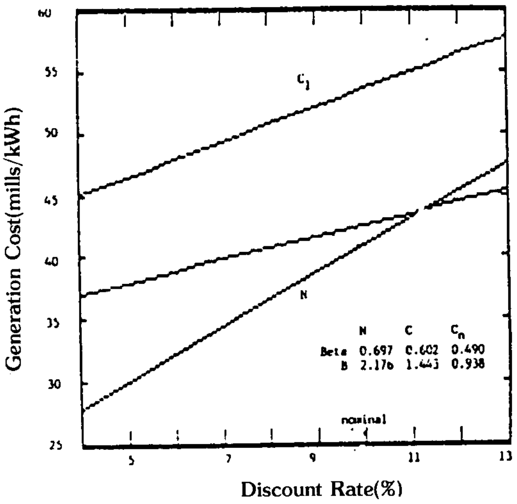


**Fig Ⅳ. One-Variable-At-A-Time Sensitivity for Discount Rate**

### 4) Multivariate uncertainty analysis

Final goal of multivariate uncertainty analysis using simulation is to get the propagated uncertainty of figure-of-merit in the of probability distribution functions. Nominal case 1 is for sulphur content of 2 percent and nominal case 2 is 0.6 percent.'

1 Generation cost

Computation results for generation cost of each altenatives are tabulated in Table Ⅶ. the results are also shown graphically in Fig. Ⅴ and Ⅵ

The mean value of nuclear power generation cost is 41.50 mils/kWh. The shares of investment cost, fuel and O&M cost are 63.4%, 21.%, and 15.0% respectively. Coal power generation cost without the control cost has nearly the same as nuclear power generation cost. The shares for coal plant are 30.9, 56.6, and 12.6% respectively. The fuel cost share for coal power plant is nearly as high as investment cost share of nuclear power plant. When the control cost is included the generation cost of coal power plant increases by nearly 10 mills/kWh.

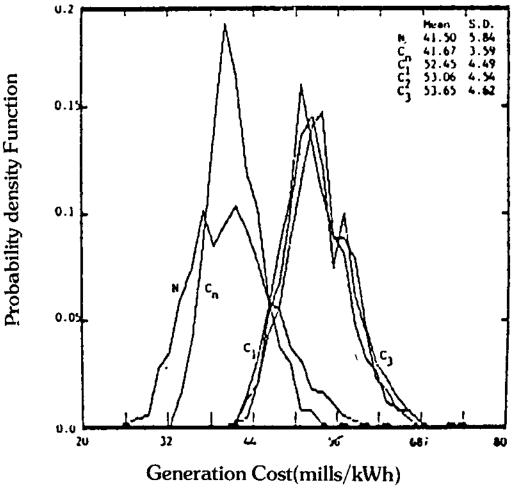


**Fig. Ⅴ Relative Probability Histogram of Levelized discounted Power Generation Costs for Nuclear and coal Power Plants With Each Scenario (Triangular Distribution Assumed for Inputs Described in Tacble Ⅸ)**

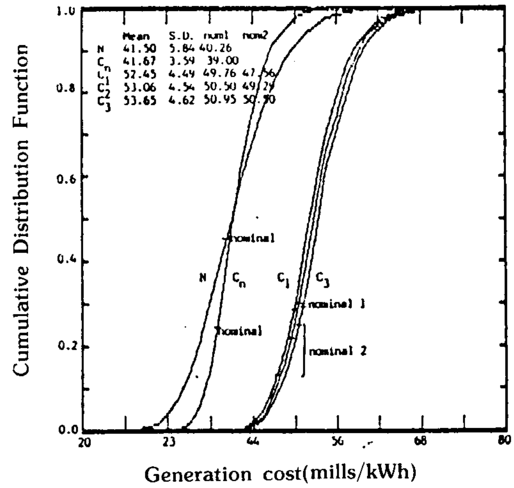


**Fig. Ⅵ Cumulative Probability Histogram of Levelized Discounted Power Generation costsfor Nuclear and Coal Power Plants with Each Scenario( Triangular Distributions Assumed for Inputs Described in Table Ⅳ)**

For triangular/point distribution 90% confidence intervals for NG, $CG_n$, $CG_1$, $CG_2$ and $CG_3$ are 32.6-51.9, 36.3-48.3, 45.5-60.5, 46.0-61.1' and 46.4-61.8 mills/kWh, respectively, as shown in Table Ⅷ.

2 Control cost

Control cost' calculation result for each scenario is summarized in Table Ⅸ. Its probability distributions are shown in Fig.Ⅶ andⅧ. Control costs vary 9.3 mills to 10.4 mills/kWh for scenario Ⅰ,Ⅱ, and Ⅲ. These are

**Table Ⅵ : Beta Coefficients**

| Variable | NG | $CG_1$ | $CG_n$ |
|---|---|---|---|
| DC | 0.679 | 0.602 | 0.490 |
| CN | 0.545 | 0.580 | 0.701 |
| FER | 0.067 | 0.209 | 0.254 |
| CF | -0.395 | -0.391 | -0.321 |
| HR | N.A. | 0.193 | 0.182 |
| IDC | 0.167 | 0.058 | 0.072 |
| LIFE | -0.148 | -0.075 | -0.059 |
| FP | 0.046 | 0.152 | 0.185 |
| LT | 0.102 | N.A. | N.A. |
| VOP | 0.088 | 0.097 | 0.117 |
| CR | 0.055 | 0.109 | 0.109 |
| S | N.A | 0.104 | N.A. |
| VOER | 0.042 | 0.079 | 0.057 |

**Table Ⅶ Generation Cost Calculation Results(mills/kWh)**

| | Item | Invest | Fuel | O&M | Total |
|---|---|---|---|---|---|
| Nuclear | mean | 26.294 | 8.963 | 6.240 | 41.497 |
| | % | 63.4 | 21.6 | 15.0 | 100 |
| | S.D. | 5.928 | 0.483 | 0.564 | 5.843 |
| Coal(n) | mean | 12.822 | 23.606 | 5.246 | 41.673 |
| | % | 30.9 | 56.6 | 12.6 | 100 |
| | S.D. | 3.486 | 1.376 | 0.494 | 3.589 |
| Coal(1) | mean | 19.173 | 24.424 | 8.850 | 52.449 |
| | % | 36.6 | 46.6 | 16.9 | 100 |
| | S.D. | 4.413 | 1.438 | 0.705 | 4.491 |
| Coal(2) | mean | 19.630 | 24.479 | 8.951 | 53.060 |
| | % | 37.0 | 46.1 | 16.9 | 100 |
| | S. D. | 4.486 | 1.440 | 0.676 | 4.538 |
| Coal(3) | mean | 20.161 | 24.504 | 8.989 | 53.654 |
| | % | 37.6 | 45.7 | 16.8 | 100 |
| | S.D. | 4.564 | 1.442 | 0.672 | 4.615 |

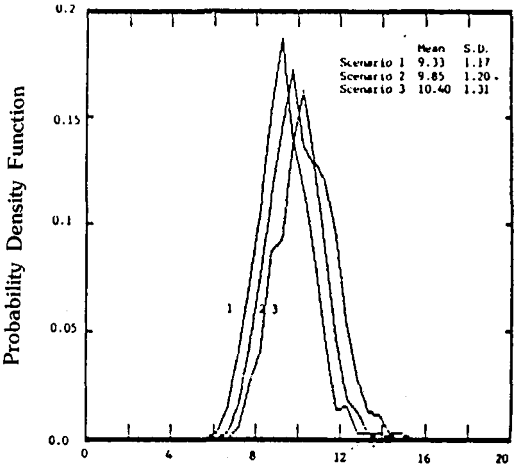


Fig. Ⅶ Relative Probability Histogram of Pollution control Cost for Each Regulation Scenario(Triangular Distributions Assumed For Inputs Described in Table Ⅸ)

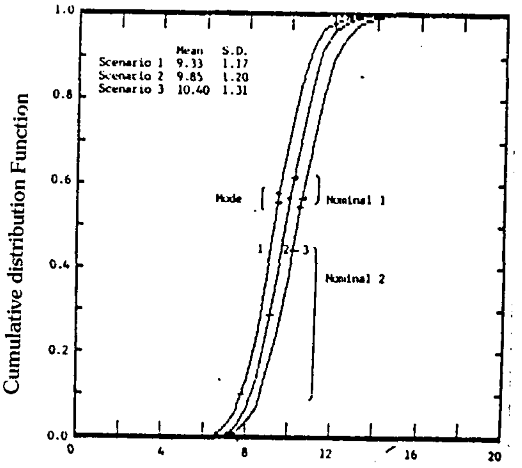


Fig. Ⅷ Cumulative Probability Histogram of Pollution Control Cost for Eac Scenario(Triangular Distributions Assumed for Inputs described in Table Ⅸ)

**Table Ⅷ : 90 percent Confidence Intervals for Generation Costs(mills/kWh)**

| | Uniform | | Triangular | |
|---|---|---|---|---|
| | interval | mean | interval | mean |
| NG | 30.136-57.429 | 42.478 | 32.550-51.887 | 41.497 |
| $CG_n$ | 35.675-52.189 | 43.210 | 36.300-48.308 | 41.673 |
| $CG_1$ | 44.523-65.260 | 53.965 | 45.504-60.511 | 52.446 |
| $CG_2$ | 45.149-66.089 | 54.654 | 46.027-61.118 | 53.059 |
| $CG_3$ | 45.662-66.897 | 55.303 | 46.409-61.849 | 53.653 |

**Table IX : Control Cost for each Scenario(mills/kWh)**

| Scenario | I | II | III |
|---|---|---|---|
| FGD Invest. (S=2%) | 214.5 | 235.9 | 246.7 |
| (Dollar/kW)* (S=0.6%) | 165.1 | 197.2 | 223.6 |
| median | 9.304 | 9.821 | 10.369 |
| mode | 9.0-9.5 | 9.5-10.0 | 10.0-10.5 |
| mean | 9.332 | 9.848 | 10.396 |
| 90% confidence interval | 7.377-11.272 | 7.880-11.799 | 8.296-12.559 |
| S.D. | 1.172 | 1.203 | 1.308 |
| % of CG(x) | 17.8 | 18.6 | 19.4 |

about 18-20% of total power generation cost.

To see the effect of sulphur content on the control cost, two nominal cases are calculated. Sulphur content change from 0.6% to 2% increases the control cost by about 1.6 mills/kWh for scenario I. 1.4 percent increase in sulphur content results in 30% increase (214.5/165.1=1.3) of investment cost for scenario I. But for more stringent regulation scenario, the difference is not so great.

As shown in Fig IX control cost for $SO_x$ is composed of 4 parts : Fixed cost, Variable cost, Power cost and Waste disposal cost. $SO_x$ control cost trend shows the same trend as fixed cost which is major variable for $SO_x$ control cost. Other three cost components are nearly constant regardless of $SO_x$ emission level variations. FGD investment cost, which is proportional to the fixed cost, shows nearly semi-linear trend with respect to $SO_x$ emission level as expected. Fixed cost is 26 mills/kWh, and variable cost, power cost, waste disposal cost are approximately 3,1,1 mills per kWh, respectively.

FGD investment cost, fixed cost term of control cost for $SO_x$, is determined assuming that the FGD system efficiency must meet the most stringent regulation expected during the FGD operation (or plant lifetime). Therefore, the FGD investment cost for each scenario is one corresponding to the regulation level of the third decade. This is why the investment cost is large more or less. The investment cost is nearly 40% of power plant investment cost. As the regulation become stringent, the probability distribution shows shift by nearly 0.5 mills/kWh. It is true of mode and mean. When assumed triangular/ point distribution, the 90% confidence intervals for the pollution control costs with each scenarios are 7.4-11.3, 7.9-11.8, and 8.3-12.6 mills/ kWh, respectively.

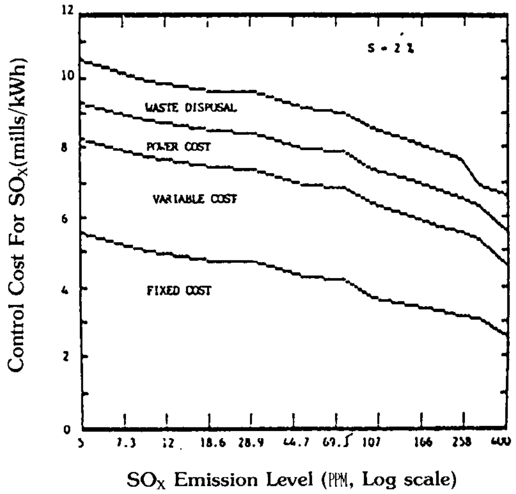


Fig IX. Control Cost for $SO_X$ Regulation Level Using FGD (S=2%)

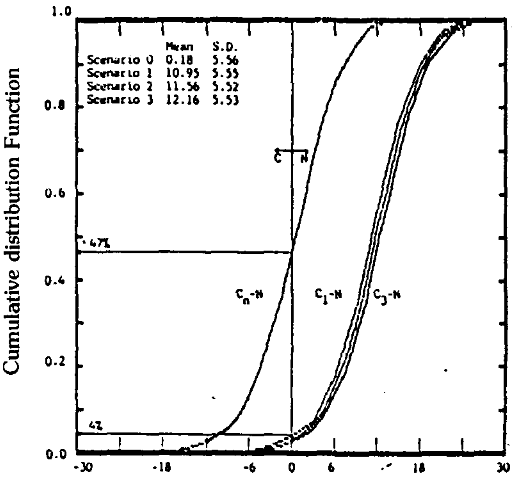
3 differential generation cost

Differential generation cost between coal nuclear power plant is summarized in Table X and represented schematically in Fig. X. Because coal power generation cost without any pollution control cost is nearly equal to nuclear power generation cost, the difference between coal and nuclear generation cost is mainly due to environmental pollution control cost of coal power plant.

In the differential generation cost distribution assuming triangular/point distribution, the percentiles cor-

**Table Ⅹ Differencial Generation Cost (CG(x)-NG, mills/kWh)**

| Scenario | 0 | Ⅰ | Ⅱ | Ⅲ |
|---|---|---|---|---|
| mean | 0.176 | 10.952 | 11.564 | 12.157 |
| mode | (-1.5)-0<br>1.5-3.0 | 9-10.5<br>12.0-13.5 | 10.5-12.0<br>13.5-14.0 | 10.5-12.0.<br>13.5-140.0 |
| 90% confidence | | | | |
| (triangular/point) | (-9.56)-8.95 | 1.05-19.87 | 1.83-20.37 | 2.42-21.13 |
| (uniform) | (-14.36)-13.30 | (-2.73)-24.29 | (-1.82)-25.28 | (-1.21)-24.87 |
| Standard Deviation | 5.562 | 5.548 | 5.519 | 5.529 |



**Differential Generation Cost (CG(x)-NG, mills/kWh)**

**Fig. Ⅹ Cumulative Probability Histgram of Differential Generation Costs Between Coal with Each Scenario and Nuclear (Triangula Distributions Assumed for Inputs Described in Table Ⅸ)**

responding zero difference are 47% for $CG_n$-NG, and for CG-NG, the percentiles are 4%, 3%, and 3%. Therefore nuclear power plant is more economical with the confidence level of 96% even in scenario Ⅰ. In scenario I, the difference lies between 1.0 and 19.9 mills/kWh with 90% confidence.

4 Uncertainty

As shown in Table Ⅶ, the uncertainty (standard deviation) of generation cost is more or less larger for nuclear than for coal. The major uncertainty contributor is investment cost for both nuclear and coal power plant. But fuel cost uncertainty is considerably large for coal power plant.

## 6. Conclusion

The conclusions from this study are as follows:

1. Control cost reaches 9-11 mills with standard deviation of 1.3 mills/kWh. 90% confidence interval is 7.4-11.3 mills/kWh for scenario Ⅰ. The cost is nearly 20% of generation cost but the FGD investment cost is nearly 40% of plant investment cost.
2. Nominal generation costs for NG and CG are slightly lower than the mean or median, which means the nominal inputs are optimistic somewhat.
3. 90% confidence interval for nuclear power generation cost is 30.1-57.4 and 32.6-51.9 mills/kWh for uniform and triangular/point distribution assumed. For coal power generation cost with each scenario when assumed triangular/point distribution assumed, the intervals are 45.5-60.5, 46.0-61.5, and 46.4-61.8 mills/kWh, respectively.
4. Most sensitive parameters are discount rate for both coal and nuclear.
5. Imporant parameters are constuction forecost, capacity factor for both nuclear and coal. For nuclear, interest rate during construction and lifetime is important. Fuel price and fuel escalation rate is important for coal.
6. Investment cost is a major uncertainty contributor for nuclear but fuel cost for coal.
7. In the case of stringent regulation, nuclear is far more economic than coal with nearly 95% confidence. *The differential generation cost for scenario* I ranges from 2.73 to 24.29 with mean of 10.95 mills/kWh at 90% confidence.

## References

1. Hamilton, L.D. "Health and environmental risks of energy systems", IAEA-SM-273/51, in 'Risks and Benefits of Energy Systems', p.23, IAEA, Vienna, 1984.
2. A Novegno, F. Neihaus, "Risk management for energy safety policy," IAEA-SM-273/43, in 'Risks and Benefits of Energy Systems', p.384, IAEA, Vienna, 1984.
3. OECD, "The state of the environment 1985," p. 117, OECD, Paris, 1985.
4. OECD, "Emission standards for major air pollutants", p.61, 1984.
5. Korea Ministry of Science and Technology, "Environmental and Economic Analysis of Nuclear and Coal-Fired Power Generation," KAERI/RR-533/8 5, p.317, 1986.
6. Korea Ministry of Energy and Resources, "Long-term Electric Genration Expansion Plan (a Proposal)," 1987.(in Korean)
7. John C.Molburg and Edward S.Rubin, "Air Pollution Control Costs for Coal-to-Electricity Systems," Journal of Air Pollution Control Association, vol. 33, No.5, p.523, 1983.
8. The Bank of Korea, "Economic Statistics Yearbook," P.1129, Seoul, 1987.
9. IAEA, "Expansion Planning for Electrical Generation Systems : A Guidebook," Technical Report Series No.241, p.151, IAEA, Vienna, 1984.
10. KAIST, "Comparative Evaluation of Nuclear and Coal-Fired Power Plants," Appendix, p.62, Dept. of Management science, KAIST, 1986.(in Korean)
11. C.Park and M.Khatib-Rahbar, "Quantification and uncertainty analysis of source terms of several accidents in Light Water Rectors (QUASAR)," Part I-Methodology and program plan, NUREG/CR-4688, p.19, 1986.
12. Kent A. Williams and Jerry G. Delene, "Probabilistic Projection of Nuclear and Coal Electric Power Generation Costs," ANS transaction, vol. 55, p.564, 1987.
13. Kent A. Williams, J.G.Delene, L.C.Fuller, H.I. Bowers, "Nuclear Economics 2000 : Deterministic and Probabilistic Projections of Nuclear Coal Electric Power Generation Costs for the Year 2000, ORNL-6368, p.24, Oak Ridge Nat'l Lab, (June 1987).
14. M.D.Makay, W.J.Conover, and R.J.Beckman," A comparison of three methods for selecting values of input variables in the analysis of output from a computer code," Technometrics, vol.21, 1979
15. Marija J. Norusis, "SPSS/PC+user's manual for the IBM PC/AT/XT," p.B-219, 1986.
16. A.Kinoshita, "Indicative environmental control cost estimates for electric utility coal use by emission standards," in 'Costs of Coal Pollution Abatement : Results of an international symposium,' edited by E.S.Rubin and Ian M.Torrens, P.120, OECD, 1984.
17. Electric Power Development Company,"Case Studies on Environmental Controls for Coal-fired Power Plants in Japan", in 'Coal Use and the Environment,' Book C, vol.2, p.57C, OECD/NEA, Paris, 1983.
18. OECD, "Coal and Environmental Protection : Costs and Costing Method,"p.80, 1983.