APPENDIX: MODEL DESCRIPTION

As stated in the text, the acid deposition regulation model presented here is of the electric utility industry in the eastern 31 states of the U.S. for 1981. The model is similar but somewhat simpler than the variety of other models of the electric power and coal industries that have been developed in recent years (e.g., ICF, 1976; Kolstad & Wolak, 1983; Zimmerman, 1981).

In each of the thirty one states of concern in the model, two types of electricity generation are considered. One type is coal-fired electricity generation without any sort of flue-gas-desulfurization (FGD) equipment. The other type is coal-fired generation capacity with some sort of FGD equipment. All coal-fired capacity within a state is aggregated into one of these two categories. One constraint on the model is that total generation within a state from both types of capacity equals 1981 coal-fired generation. The model chooses how much to operate each type of capacity, where to buy fuel from and the amount, if any, of FGD retrofit.

Turning to a mathematical description of the model, Table A-I presents a summary of indices and variables used in the model. The objective function is to minimize total costs of generating electricity:

$$\min \sum_{j\ell}\sum \left\{\sum_i (p_i + \tau_{ij}) z_{ij\ell} + f_{j\ell}(k_{j\ell}, s_{j\ell}, e_{j\ell})\right\}. \qquad \text{(A-1)}$$

The first term in braces above represents fuel costs. The second term represents the one-year opportunity cost of FGD retrofit capital. The function $f_{j\ell}$ will be discussed later in more detail.

The minimization of eqn. (A-1) is subject to a number of constraints. One is that electricity generated in each region be at least equal to 1981 coal-fired generation:

$$\sum_{\ell} y_{j\ell} \geq \bar{y}_j \qquad , \forall_j . \qquad \text{(A-2)}$$

Related to this is a set of production feasibility constraints that a) generation in megawatt-hours be consistent with capacity in megawatts; b) that fuel use be consistent with generation; c) that the identity defining sulfur use be satisfied; and d) that existing FGD equipment, if any, be fully utilized.

$$\frac{y_{j\ell}}{8.76k_{j\ell}} \leq \sigma_{j\ell} \qquad , \forall_{j,\ell} \qquad \text{(A-3)}$$

$$\sum_{i} z_{ij\ell} \geq h_{j\ell}\, y_{j\ell} \qquad , \forall_{j,\ell} \qquad \text{(A-4)}$$

$$s_{j\ell} \equiv \sum_{i} \rho_i\, z_{ij\ell} \qquad , \forall_{j,\ell} \qquad \text{(A-5)}$$

$$\frac{e_{j\ell}}{2s_{j\ell}} \leq \bar{X}_{j\ell} \qquad , \forall_{j,\ell} \qquad \text{(A-6)}$$

A final set of constraints concerns environmental regulations. Of course a regulation requiring the use of FGD would be identical to equation (A-6) above with $\bar{X}_{j\ell}$ replaced by one minus the legislated minimum SO_2 removal rate. However, the typical legislated SO_2 regulation concerns the sulfur dioxide emission rate per unit of fuel use. Current regulations on old power plants ("SIP's") are often of this form, regulations for new plants are of this form and most acid rain legislation propose limits of this form:

$$\frac{e_{j\ell}}{\sum_i z_{ij\ell}} \leq \bar{e}_{j\ell} \qquad , \forall_{j,\ell} \qquad \text{(A-7)}$$

In the model we include SIP and NSPS regulations of this form on existing plants. A final set of environmental regulations are the emission-oriented and receptor-oriented regulations for controlling deposition. As Montgomery (1971) has shown, a marketable permit system for implementing such regulations may be reflected by appending constraints to the minimization problem. An ambient differentiated permit system to achieve a deposition rate of $\bar{\delta}$ can be represented by

$$\sum_j a_j \sum_\ell e_{j\ell} \leq \bar{\delta}. \qquad \text{(A-8)}$$

Two types of emission-oriented permits can be considered. One would involve interstate and intersource trading. A permit issuance of $\hat{e}$ could be represented by

$$\sum_{j\ell}\sum e_{j\ell} \leq \hat{e}. \qquad \text{(A-9)}$$

If only inter-source but not interstate trading is permitted then if $\tilde{e}_j$ permits are issued in each state, a permit system would operate according to

$$\sum_\ell e_{j\ell} \leq \tilde{e}_j. \qquad \text{(A-10)}$$

The scrubber cost function, $f_{j\ell}$, is taken directly from Atkinson (1983). Based on an econometric analysis of actual scrubbers, he reports annual scrubbing costs (thousands of dollars) of

$$C = \underset{(573)}{430.629} + \underset{(.017)}{.32188} \cdot PR \cdot MW + \underset{(.015)}{.46474} \cdot PR^2 + \underset{(.261)}{2.881} \cdot PS \cdot MW \qquad \text{(A-11)}$$

where MW is the unit size in megawatts, PR is the percent sulfur removal, PS is the percent sulfur in the fuel and numbers in parentheses are standard errors associated with the estimated coefficients. We assumed a unit size of 500 MW and fixed fuel sulfur control of 5%. An upper limit of 100 was assumed for PR. Thus $f_{j\ell}$ becomes

$$f_{j\ell} = \{15.266 + 32.188\ (1 - \frac{e_{j\ell}}{2 \cdot s_{j\ell}}) + 9.295\ (1 - \frac{e_{j\ell}}{2 \cdot s_{j\ell}})^2\} k_{j\ell}.$$

Because this function is fairly linear, controlcosts for high removal rates are probably understated.

Data for the model are reported in Tables A-II and A-III and come from a variety of sources. The atmospheric transport coefficients are from the U.S.-Canada working group on acid deposition (Schiermeir and Misra, 1982). The coefficients used here represent the mean values for the eight atmospheric transport models examined by the working group and refer to deposition at a receptor in the Adirondacks. Electricity production from coal is from the Electric Power Annual (US DOE 1982b). Heat rates (h), availabilities (σ) and capacity levels (k) are from a unitby-unit data base (Generating Unit Reference File--GURF) described in Wolak et al (1981). Default availabilities and heat rates of .70 and 9.5, respectively were used for plants for which no data were available. Existing emission control levels ($\overline{X}_{j1}$) are from US DOE (1982a) and SIP control levels are as reported by Pechan Associates to the EPA (personal communication, Willard Smith, USEPA, 1983). Coal prices and characteristics are from US DOE (1982a,c). Coal transport rates are from Kilkeary, Scott Assoc. (1983).

TABLE A-I: INDICES, VARIABLES, PARAMETERS, AND FUNCTIONS

INDICES

$i = 1, \ldots, 14$	Coal Producing Regions
$j = 1, \ldots, 14$	Coal Combustion Regions
$\ell = 1, 2$	Electricity Generation Technology Types

ENDOGENOUS VARIABLES

$z_{ij\ell}$	Coal from region i consumed in region j in technology ℓ (10^{12} Btu)
$y_{j\ell}$	Electricity output in region j from technology ℓ (10^9 Kwh)
$e_{j\ell}$	SO_2 emissions from technology ℓ in region j (10^6 lb)
$s_{j\ell}$	Sulfur burned in technology ℓ in region j (10^6 lb)

PARAMETERS

ρ_i	Sulfur content of coal from region i (lb./10^6 Btu)
τ_{ij}	Transport cost for coal from region i to region j (\$/10^6 Btu)
p_i	Price of coal in region i (\$/10^6 Btu)
$k_{j\ell}$	1981 capacity of type ℓ in region j (GW)
$\sigma_{j\ell}$	Availability of capacity type ℓ in region j (fraction)
$\bar{y}_j$	1981 coal-fired electricity generation in region j (10^9 Kwh)
$\bar{e}_{j\ell}$	SO_2 emission limit for technology ℓ in region j (lb./10^6 Btu)
$\bar{X}_{j\ell}$	One minus lower bound on sulfur removal efficiency for technology ℓ in region j
$h_{j\ell}$	Heat rate for technology ℓ in region j (10^3 Btu/Kwh)
a_j	Transfer coefficient from region j (gS/hectare/10^6 lb SO_2)

FUNCTIONS

$f_{j\ell}$	Cost of FGD control of technology ℓ in region j (10^6 \$)

TABLE A-II: Data Assumptions for Coal Combustion Regions

j	Region	a_j	$\overline{y}_j$	σ_{j1}	$\sigma_{j\ell}$	h_{j1}	h_{j2}	k_{j1}	k_{j2}	SIP Limits ($e_{j\ell}$) $\ell=1$	SIP Limits ($e_{j\ell}$) $\ell=2$	$\overline{X}_{j1}$
1	Pennsylvania	0.75	91.9	0.73	0.68	10.3	10.3	3.1	14.2	0.92	3.05	0.90
2	Ohio	0.45	106.8	0.68	0.71	10.9	10.3	0.75	20.8	5.66	5.0	0.89
3	New York	1.98	14.4	—	0.77	—	10.8	—	2.4	—	3.36	—
4	Indiana	0.22	66.4	0.72	0.71	10.1	10.2	0.84	13.1	1.20	5.05	0.85
5	West Virginia	0.44	72.6	0.68	0.70	9.5	9.9	1.2	13.0	1.20	3.45	0.90
6	NJ/DE/MD/DC	0.45	24.2	—	0.66	—	9.9	—	5.0	—	2.17	—
7	Massachusetts	0.45	2.3	—	0.83	—	9.6	—	0.64	—	0.70	—
8	Michigan	0.42	53.2	—	0.68	—	10.4	—	10.5	—	2.09	—
9	MO/IL	0.12	110.4	0.71	0.69	11.0	10.6	3.0	21.7	1.71	4.81	0.81
10	Kentucky	0.17	57.1	0.77	0.69	10.2	9.6	4.4	8.6	1.27	3.90	0.88
11	Tennessee	0.09	48.1	—	0.67	—	10.0	—	9.3	—	3.79	—
12	VA/NC/SC	0.12	99.0	0.70	0.75	9.7	9.8	0.81	16.0	1.97	2.42	0.72
13	AR/LA/MS/AL/GA/FL	0.03	135.4	0.63	0.70	10.5	10.3	1.8	26.5	1.20	3.65	0.67
14	MN/WI/IA	0.12	64.0	0.76	0.75	10.3	11.0	2.2	13.8	2.45	3.55	0.63

TABLE A-III: Data Assumptions for Coal Production and Transport

Region	p_i	ρ_i	$\tau_{ij}, j =$ 1	2	3	4	5	6	7	8	9	10	11	12	13	14
Maryland	1.30	1.56	4.62	5.63	5.89	7.14	6.07	4.82	9.16	6.74	9.33	6.92	*	*	*	9.07
West Penn.	1.28	1.75	3.68	4.83	5.50	6.50	4.99	5.19	8.72	5.89	8.48	7.16	*	*	9.69	8.23
North West Va.	1.27	1.83	5.29	5.73	6.88	6.64	4.62	5.96	10.50	7.54	9.10	6.36	7.90	*	9.43	8.28
Ohio	1.28	2.98	3.97	3.43	6.60	4.92	5.09	6.49	9.00	4.96	7.04	5.45	6.53	*	7.80	6.81
Panhandle, WV	1.34	3.15	5.29	5.73	6.88	6.64	4.62	5.96	10.50	7.54	8.10	6.36	7.90	*	9.43	8.28
East Kentucky	1.44	0.91	6.53	4.73	*	6.16	6.97	8.21	*	6.61	8.63	4.70	5.34	7.77	6.16	8.35
Tennessee	1.20	1.31	8.41	5.97	8.89	6.60	9.66	8.17	12.80	7.50	9.07	5.77	4.48	6.72	5.33	8.79
Virginia	1.40	0.80	10.10	8.11	8.34	*	11.53	7.56	12.17	9.97	11.54	8.18	6.72	8.85	7.48	11.26
South West Va.	1.57	0.74	6.11	4.50	7.77	6.03	6.49	6.94	11.52	6.37	8.49	5.35	7.64	9.96	8.82	8.21
West Kentucky	1.21	2.90	*	4.52	9.12	4.40	*	*	*	5.59	5.93	3.94	4.34	8.91	4.51	5.96
Illinois	1.26	2.46	*	4.26	*	4.29	*	*	*	5.23	3.56	4.02	5.22	*	5.51	4.95
Indiana	1.06	2.38	*	3.80	*	3.51	*	*	*	4.74	4.66	3.29	4.45	*	4.58	4.91
Alabama	1.67	1.16	8.41	5.97	8.89	6.60	9.66	8.17	12.80	7.50	9.07	5.77	4.82	7.21	4.36	8.79
Wyoming	0.68	0.46	20.09	14.41	21.18	14.84	24.12	22.39	21.12	15.01	14.18	15.69	16.61	26.74	16.18	14.29

Assumed to be an uneconomic transport link