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Abstract

The Commonwealth of Massachusetts promulgated an Act limiting SO_2 emissions from large sources that burn fuel at a rate greater than or equal to 100 million Btu (MBtu) of fuel input per hour. The Act requires that by 1995 the average emission rate at such facilities be less than or equal to 1.2 lb SO_2 per MBtu fuel input. Because of their size, almost all power plants in Massachusetts could be subject to emission reductions. Since the average 1980-1982 annual emission rate of Massachusetts power plants was 1.84 lb SO_2/MBtu ("base case"), the Act requires the annual average emission rate of power plants to diminish by 35%.

We use a source apportionment model to estimate the wet sulfate deposition to typical sensitive Massachusetts receptors from Massachusetts power plants, separately for the summer (April-September) and winter (October-March) half-years. We find that the summer wet deposition is about twice the winter deposition, although summer and winter SO_2 emissions are approximately equal. Therefore, to reduce sulfate deposition, it is more effective to reduce emissions in the summer months rather than in winter. Using the seasonal source apportionment model we find that an annual wet deposition reduction equal to that resulting from the Act could be accomplished if only summer emission rates were reduced to 0.86 lb SO_2/MBtu, with winter emission rates remaining at 1.84 lb SO_2/MBtu. The resulting annual average emission rate is 1.35 lb SO_2/MBtu, 27% less than the base value. As 1980-1982 average annual emissions from power plants amounted to 270,000 tons of SO_2 annually, a summer emission control program would save about 21,000 tons of SO_2 emission reduction without sacrificing wet deposition protection. The summer emission reduction could be acomplished by substituting lower sulfur content fuels, including natural gas, for higher sulfur content fuels.

Introduction

The Commonwealth of Massachusetts promulgated an Act (Chapter 590, 1985) limiting SO_2 emissions from large sources that burn fuel at a rate greater than or equal to 100 million British thermal units (MBtu) of fuel input per hour. The Act requires that by 1995 the average emission rate at such facilities be less than or equal to 1.2 lb SO_2 per MBtu of fuel input. As the 1980-1982 average annual emission rate at Massachusetts power plants amounted to 1.84 lb SO_2 per MBtu, which we use here as a base, the Act would require that by 1995 the power plants reduce their average emission rate by 35%.

The purpose of this report is to compare, by means of atmospheric modeling, the deposition of sulfate ions in precipitation at typical Massachusetts receptors resulting from the emissions of Massachusetts power plants using several scenarios of emission reduction. We first estimate the deposition resulting from the base case emission rates; second, the deposition that would result upon implementation of the Act; and third, if emissions were reduced only in the summer half of the year to a rate which would produce equal annual deposition rates as the implementation of the Act.

It is shown that summer emission reduction is more effective in reducing annual deposition rates than winter emission reduction. This is consistent with actual deposition measurements in Massachusetts (and atmospheric modeling, which is based on the measurements) indicating that summer wet sulfate deposition is at least twice the winter deposition. Accordingly, removing a unit of power plant emissions in the summer half of the year is more effective in reducing annual depositions than removing the same unit of emissions spread over the entire year.

Emissions

There are 8 major power plants (most have several generating units) in Massachusetts. For this study, the emissions were organized into 5 emission centroids. These plants and centroids are shown in Figure 1. The 1980-82 average annual emissions (ton SO2), heat input (MBtu) and emission rates (lb SO_2 per MBtu) are listed in Table I (Kaplan, 1986). It is assumed that summer half-year (October through March) and winter half-year (April through September) emissions and emission rates are equal. This is generally valid throughout the northeastern states as electricity demand is relatively constant over the year. The power plants' total annual emissions amounted to

269 kTy^{-1} which is about 66% of total state emissions of SO_2. The annual average (weighted) power plant emission rate in 1980-1982 was 1.84 lb SO_2 per MBtu.

Receptors

Three receptors in Massachusetts were selected, thought to be sensitive to acid deposition because of the low alkalinity of their surface waters: Turners Falls (TFL) in the northwestern region, Brewster (BRW) on Cape Cod and Gloucester (GLC) in the northeastern region. The receptors are marked in Figure 1. In Turners Falls there is a high-quality continuously operating acid deposition monitor, sponsored by the Utilities Acid Precipitation Study Program; its data are recorded by the National Acid Deposition System. In the years 1980-82, the average annual wet sulfate deposition at Turners Falls was 23.3 kg $SO_4^{=}$ $ha^{-1}y^{-1}$. In this report we are considering only Massachusetts power plant sources, so no direct comparison is possible with measurements, as the latter reflect the cumulative total of all possible sources, near and distant.

Modeling Results

For estimating the contributions of Massachusetts power plants to the wet sulfate deposition at the selected receptors, we use the MIT Acid Deposition Model (Fay, Golomb and Kumar, 1985; Kumar, 1986). Since the model uses long-term (annual or seasonal) and long-range (scales of hundreds of kilometers) averages, difficulties are encountered when short-range source-receptor distances (in the order of tens of km) are considered. The difficulties arise because the Bessel functions of the model, which are weakly singular about $r = 0$, tend to overpredict the contribution of the primary species, SO_2, to the wet deposition at receptors near sources. We circumvent this problem by estimating only the contribution of secondary species, $SO_4^{=}$, to the wet deposition at the receptors. Generally, measurements confirm that there is very little primary SO_2 in precipitation (e.g. MAP3S/RAINE, 1982).

For modeling summer/winter deposition ratios, we first calculate the transfer coefficients (T_{ij}), relating the amount of sulfate deposited at a receptor (D_j) to the amount of SO_2 emitted at a source (Q_i):

$$D_j = T_{ij} Q_i \qquad (1)$$

The calculation of the transfer coefficients requires the specification of the amount of rainfall at the receptors for the semi-annual periods. For this modeling exercise, we used the 1980-82 average rainfalls in summer and winter in eastern North America, 55.6 and 43.2 cm, respectively. The actual average 1980-82 rainfalls at Turners Falls were 50.8 cm for summer, and 44.8 cu for winter months.

Table II lists the transfer coefficients from the emission centroids to the receptors. (A transfer coefficient is listed for Worcester, WOR, although no major power plant is located there.) The transfer coefficients are in units of grams sulfate deposited per hectare (2.47 acres) at the receptor per ton SO_2 emission at the source. Here we are mainly interested in the ratio of summer to winter transfer coefficients (bottom block of Table II), rather than in the absolute deposition amounts. These ratios are in the range 2.2 - 2.5, depending on the orientation of the receptor to the source. Upwind sources have larger transfer coefficients than downwind ones. The actual measured summer/winter deposition ratio at Turners Falls, in 1980-82, was 2.6, in good agreement with the modeled ratios.

For comparison we show in Figure 2 the ratios of empirical (measured) and predicted summer/winter wet sulfate deposition ratios at 109 eastern North America receptors, 1980-1982 averages. We see that the ratios range from 1.0 to greater than 3.5. The estimated Massachusetts summer/winter ratios are in the middle of the range.

Mitigating Strategies

The estimate of the effects of various emission roll-back strategies on wet sulfate deposition is best illustrated graphically. In order to gain an overview of these effects, emission-weighted average transfer coefficients from the power plant groups to each of the receptors were calculated. In Figure 3, the effects of emission roll-backs are illustrated for the Turners Falls (TFL) receptor. The upper horizontal line shows the annual deposition from the power plant groups emitting at their 1980-1982 average rate ("base case"). The resulting deposition is about 278 grams $SO_4^=$ per hectare per year. The lower horizontal line shows the annual deposition that would result if the power plants' average annual emission rate were reduced to 1.2 lb SO_2 per MBtu fuel input, as required by the Massachusetts Act. The deposition would decrease to about 175 grams, i.e., by 37%. The squares interconnected by the curve represent depositions from emission roll-backs at the power plants only in the summer half-year from 1.2 lb SO_2 per MBtu (right-most square) to 0.6 lb SO_2 (left-most square). The curve intersects the lower horizontal line at a summer emission rate of 0.84 lb SO_2 per MBtu.

Figure 4 illustrates the situation at the Gloucester (GLC) receptor. The scales and symbols are the same as in Figure 3. The summer emission rate that would be equivalent to the annual roll-back of 1.2 lb is 0.87 lb SO_2 per MBtu. Figure 5 relates to the Brewster (BRW) receptor. There, the equivalent summer roll-back is 0.86 lb per MBtu.

For the 3 receptors, the average base case deposition from the power plants is about 300 grams $SO_4^=$ per hectare per year; the average deposition upon implementation of the Act would be 190 grams, i.e. a deposition reduction of 37% for an average emission reduction of 35%. The nearly proportional emission/deposition reduction is a consequence of the "linear chemistry" assumption inherent in the model. As the model was validated against a very large temporal and spatial set of sources and receptors in eastern North America, the linear chemistry assumption appears to be valid.

An equivalent (37%) annual average deposition reduction at the receptors could be accomplished if the Massachusetts power plants were to reduce their emission rate only in the summer half-year to an average of 0.86 lb SO_2 per MBtu fuel heat input. On an annual average basis this represents an emission rate of (0.86 + 1.84) / 2 = 1.35 lb SO_2 per MBtu, a 27% emission reduction from base case annual rates. Thus, in term of deposition reduction, the summer emission reduction is (1.84 - 1.2) / (1.84 - 1.35) = 1.3 times as effective as the year-round emission reduction. In other words, in order to achieve the same deposition reduction, 1 ton SO_2 removed in the summer months is as effective as 1.3 tons SO_2 removed over the entire year.

Summary and Conclusions

Summarizing these results, we conclude that if the Massachusetts major power plants were to reduce their annual emissions from the base case average rate of 1.84 lb SO_2/MBtu fuel heat input to 1.2 lb (-35%), the average annual wet sulfate deposition from these sources at the 3 Massachusetts receptors would decline from the base case average of 300 gr $SO_4^=$ $ha^{-1}y^{-1}$ to 190 gr (-37%). The same annual $SO_4^=$ deposition reduction could be accomplished if summer emission rates only were reduced to an average of 0.86 lb SO_2/MBtu while winter emissions remain unchanged. This represents an annual averaged emission reduction of 27%. The 35% emission reduction specified by the Massachusetts acid rain Act requires 94 kTy^{-1} of SO_2 reduction; the summer only plan requires 27% or 73 kTy^{-1} reduction, a savings of 21 kTy^{-1} of emission control.

References

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Table I. Massachusetts Power Plants and Their Emissions

Area*	Centroid*	Power Plant	Annual Average Rates (1980-82)		
			Emissions**	Heat Input	Emission Rate
			(ton SO_2)	(MBtu)	(lb SO_2/MBtu)
Pioneer/Berkshire	(HOL)	Mt. Tom	9,890	9,140	2.16
		W. Springfield	6,775	10,032	1.35
Boston/Merrimack	(REV)	Mystic	26,818	42,716	1.26
		Salem Harbor	41,348	37,414	2.21
		New Boston	19,354	38,324	1.01
Southeast	(SOM)	Brayton Point	84,628	85,354	1.98
		Montaup	11,838	10,542	2.25
Cape Cod	(SAN)	Canal	68,786	59,022	2.33
Power Plant Total			269,437	292,544	
Weighted Average					1.84
State Total			408,615		

* Massachusetts was divided into 5 emission areas, generally based on the State Air Pollution Control Districts. Initials used for the area emission centroids are:

HOL - Holyoke

REV - Revere

SOM - Somerset

SAN - Sandwich

WOR - Worcester (no major power plant)

** Emissions are based on data of the Massachusetts Department of Environmental Quality Engineering.

Table II. Transfer Coefficients from Massachusetts Power Plants to Receptors (see Figure 1 for locations)

Wet Deposition Transfer Coefficients
(x 10^3 g-SO_4/ha * 1/ton-SO_2) Annual*

	TFL	GLC	BRW
HOL	1.21	1.16	1.04
WOR	1.14	1.20	1.09
REV	1.03	1.22	1.11
SOM	1.06	1.21	1.18
SAN	0.975	1.19	1.20

Wet Deposition Transfer Coefficients
(x 10^3 g-SO_4/ha * 1/ton-SO_2) Summer*

	TFL	GLC	BRW
HOL	1.73	1.66	1.48
WOR	1.62	1.72	1.55
REV	1.44	1.74	1.57
SOM	1.48	1.73	1.69
SAN	1.34	1.69	1.72

Wet Deposition Transfer Coefficients
(x 10^3 g-SO_4/ha * 1/ton-SO_2) Winter*

	TFL	GLC	BRW
HOL	0.692	0.656	0.604
WOR	0.669	0.680	0.628
REV	0.629	0.691	0.641
SOM	0.641	0.690	0.672
SAN	0.608	0.685	0.685

Ratio of Summer to Winter Transfer Coefficients

	TFL	GLC	BRW
HOL	2.51	2.52	2.45
WOR	2.41	2.53	2.46
REV	2.29	2.52	2.45
SOM	2.31	2.51	2.52
SAN	2.21	2.46	2.52

* - short tons (2000 lbs).

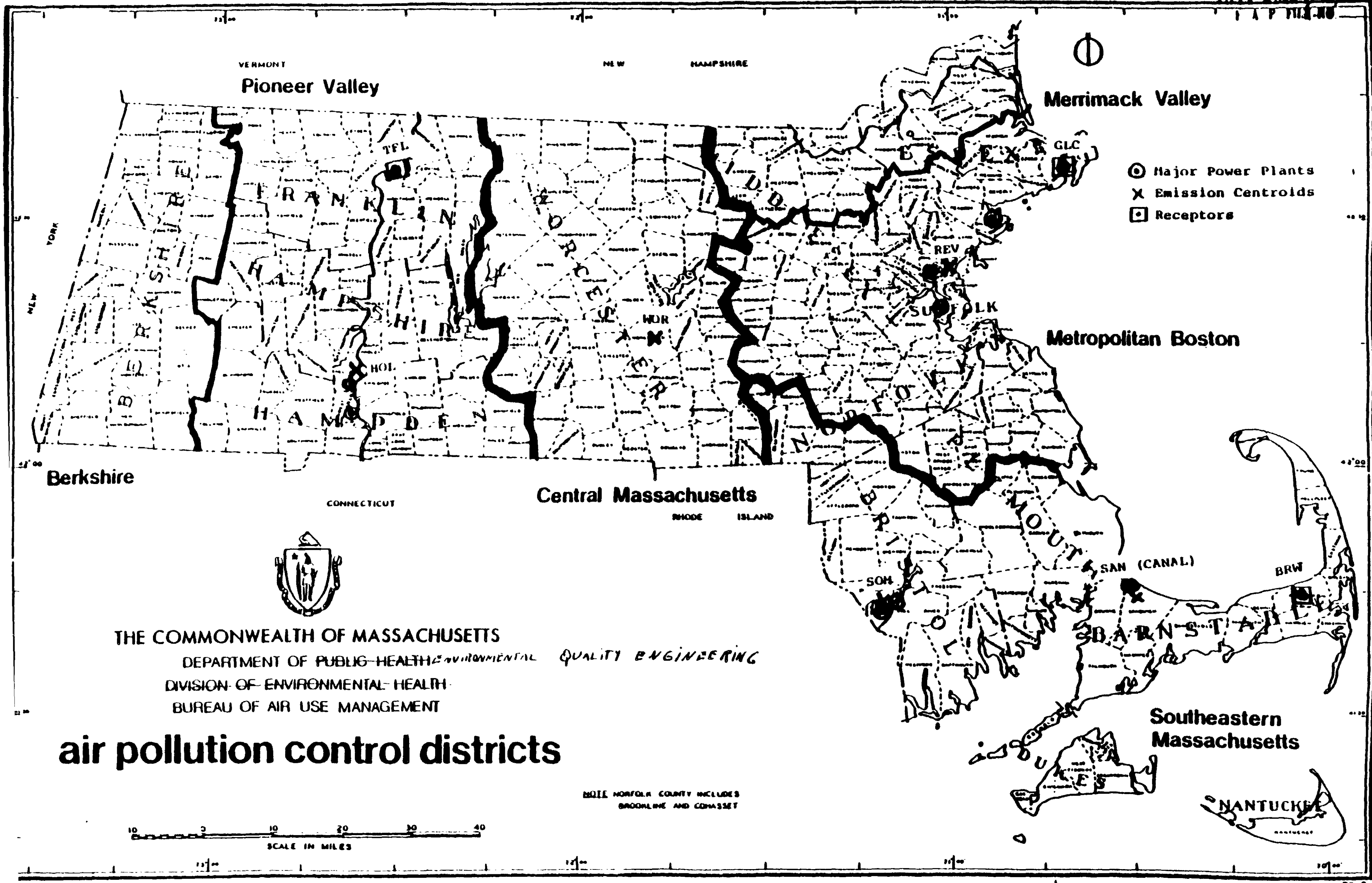
VERMONT
NEW HAMPSHIRE
Pioneer Valley
Merrimack Valley
Major Power Plants
Emission Centroids
Receptors
Metropolitan Boston
Berkshire
CONNECTICUT
Central Massachusetts
RHODE ISLAND
Southeastern Massachusetts
FRANKLIN
HAMPSHIRE
HAMPDEN
WORCESTER
ESSEX
SUFFOLK
NORFOLK
PLYMOUTH
BRISTOL
BARNSTABLE
DUKES
NANTUCKET
TFL
HOL
WOR
GLC
REV
SOM
SAN (CANAL)
BRW
THE COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF ~~PUBLIC HEALTH~~ ENVIRONMENTAL QUALITY ENGINEERING
~~DIVISION OF ENVIRONMENTAL HEALTH~~
BUREAU OF AIR USE MANAGEMENT
air pollution control districts
NOTE NORFOLK COUNTY INCLUDES BROOKLINE AND COHASSET
10 0 10 20 30 40
SCALE IN MILES

Figure 1

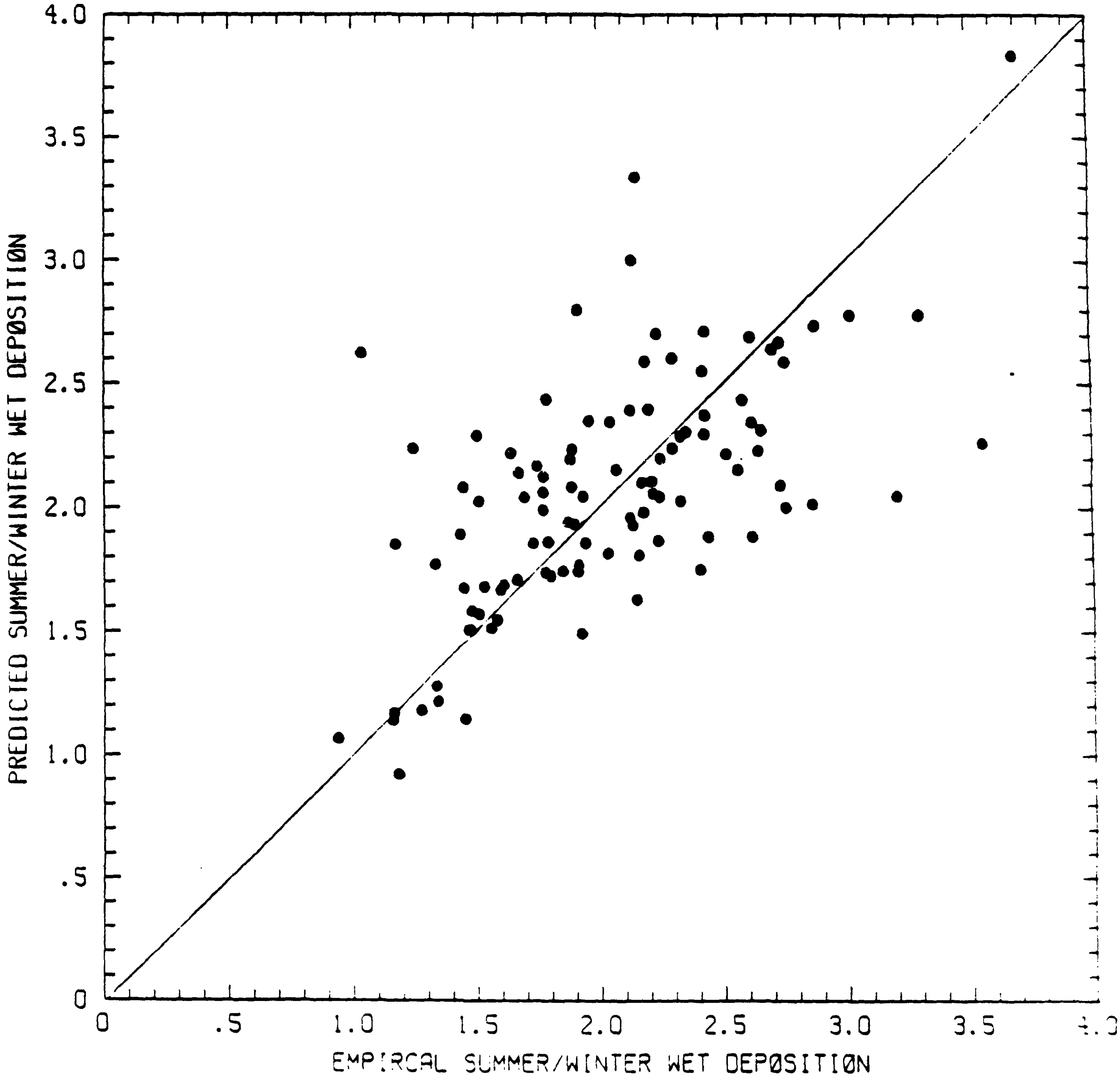

Figure 2. Ratios of summer/winter wet sulfate deposition at 109 receptors in eastern North America, 1980-1982 average. Abscissa - measurements, ordinate - modeled.

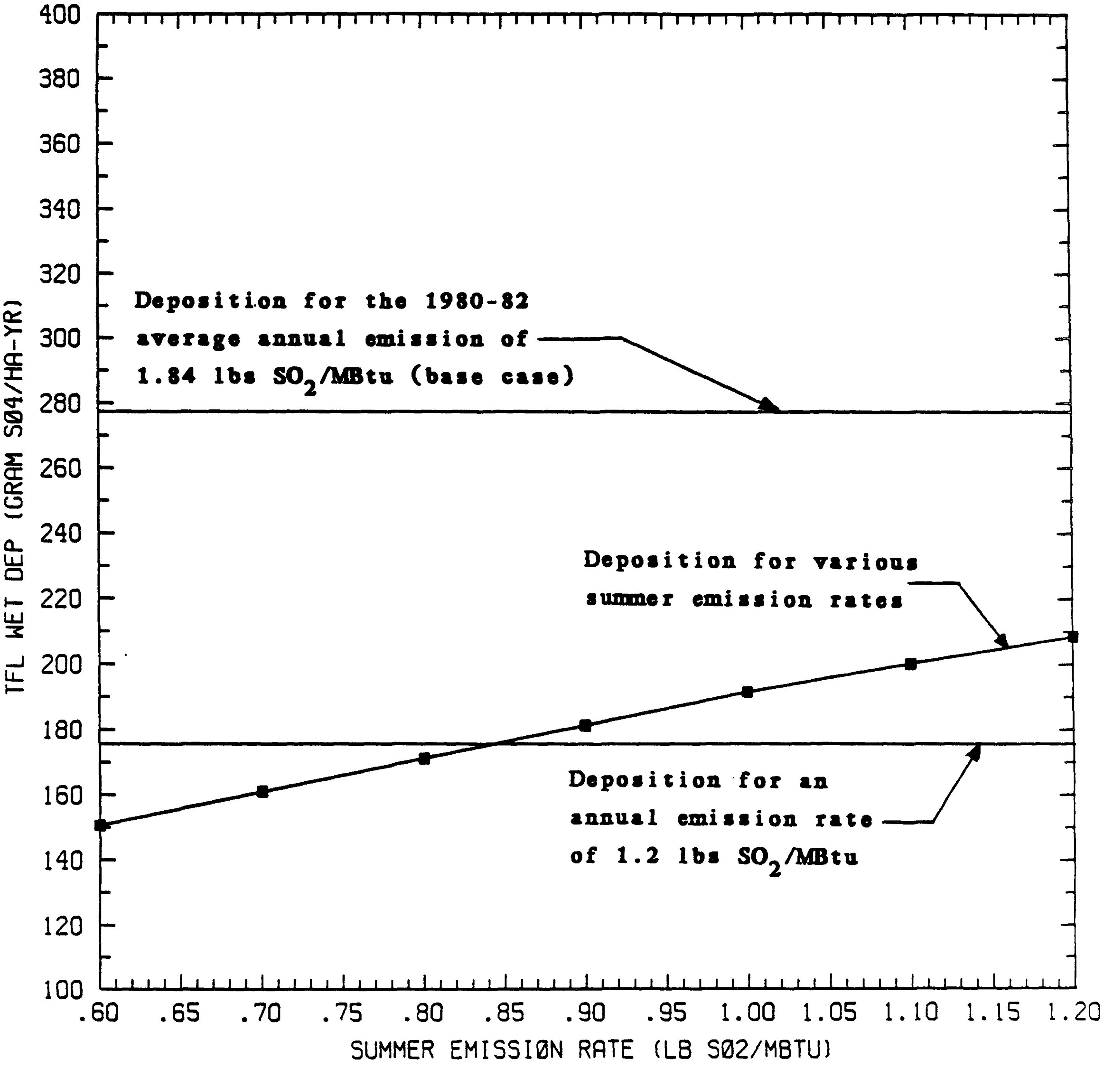

Fig. 3 Wet deposition rates (gr SO_4/ha yr) at Turners Falls, MA for various emission rates

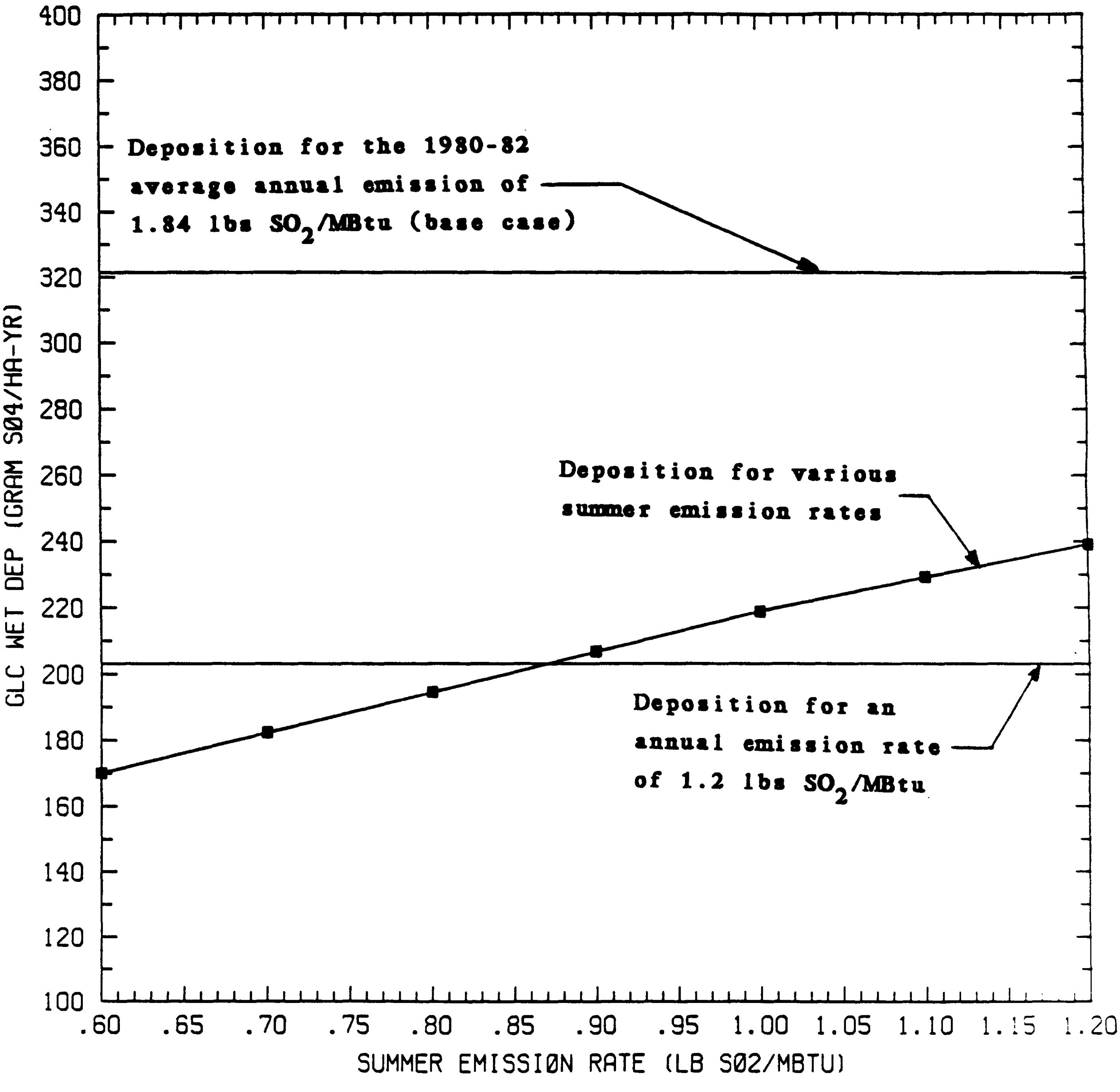

Fig. 4 Wet deposition rates (gr SO_4/ha yr) at Gloucester, MA for various emission rates

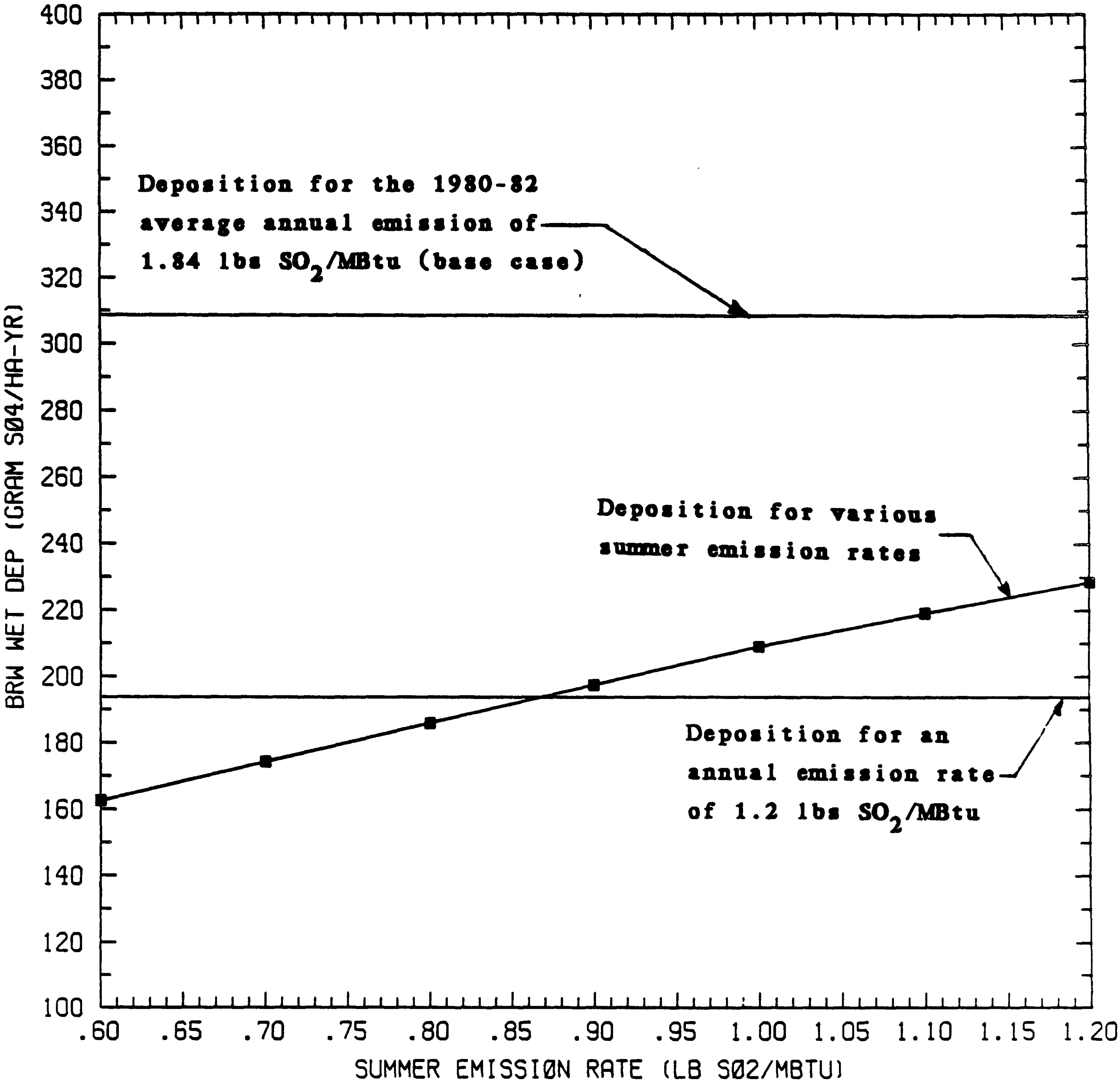

Fig. 5 Wet deposition rates (gr SO_4/ha yr) at Brewster (Cape Cod), MA for various emission rates