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Donald C. Haney, State Geologist and Director
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PREDICTING THE IMPACT OF CHANGES IN THE EPA COMPLIANCE STANDARD FOR SULFUR EMISSIONS ON THE COAL RESOURCES OF EASTERN KENTUCKY

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James C. Cobb[1], James C. Currens[1], and K. W. Teoh[2]

ABSTRACT

The abundance of compliance coal resources in the Eastern Kentucky Coal Field can be represented by a statistical probability model that relates percentage of total coal resources for eastern Kentucky to potential sulfur emissions. The model is a mixture of two Weibull distribution functions.

Predictions about potential impacts on the coal resources of eastern Kentucky may be made from the probability model. For example, the steepest gradient in the distribution curve of compliance coal resources is in the range of 0.8 to 1.1 pounds SO_2 per million Btu, where about 31 percent of the resources occur. A change in the EPA compliance standard of only 0.1 pound of SO_2 per million Btu in this critical range precludes from compliance at least 10 percent of the total resources in the coal field.

If the present EPA compliance standard for sulfur emissions were made more stringent, the viability of the Eastern Kentucky Coal Field would be in jeopardy because an extremely large percentage of resources would be removed from compliance. Therefore, the assessment of resources by probability statistics provides an understanding that is important to resource planning and policy decision making.

INTRODUCTION

Congress is currently debating reauthorization of the Clean Air Act and strategies to regulate sulfur dioxide emissions. Weighing most heavily in this debate is the controversy over acid rain and control strategies for regulating sulfur emissions from coal-burning power plants. Under the current control strategy, most new power plants must attain an emissions limit of 0.6 pound of SO_2 per million Btu, while most operating plants must attain an emissions limit of 1.2 pounds of SO_2 per million Btu, with a minimum percent reduction in sulfur for all coal burned.

There is a general lack of resource information with respect to potential SO_2 emissions. The scarcity of this information hinders the ability of government planners to formulate policies and invites the all-too-commonly-quoted generalizations about coal abundance and longevity. It is very important to consider the availability of coal resources according to emissions standards given in pounds of SO_2 per million Btu in order to formulate effective and reasonable control strategies.

The purpose of this report is to characterize the coal resources of the Eastern Kentucky Coal Field in terms of their potential sulfur dioxide emissions, using a statistical probability model. In a previous report on the compliance coal resources of Kentucky, Cobb and others (1982) characterized Kentucky resources in terms of the quantity of coal that complies with various sulfur-emissions limits. This earlier report presents details about ton-

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nages of resources, distributions of sulfur and Btu's, and sampling statistics. Presented in this current paper is a cumulative frequency distribution function that characterizes the resources for the Eastern Kentucky Coal Field by their potential sulfur emissions, and a summary of the methods used to construct a probability model. The probability-model approach to characterizing coal resources should prove useful where: (1) well-documented channel sampling of each significant coal bed has been done, (2) sample coverage is adequate to represent the coal bed, (3) sulfur and Btu data are available, and (4) tonnage estimates of the coal are up to date and well documented.

This probability model for eastern Kentucky is based upon recent detailed coal-resources data given in tons of original resources of 11 principal coal beds representing about 75 percent of the total resources for eastern Kentucky and 560 coal analyses from channel samples of these coals. Potential sulfur dioxide emissions are derived from the U.S. Bureau of Mines formula by Cavallaro and others (1976), where SO_2 emissions equal total sulfur times 20,000, divided by Btu per pound.

STATISTICAL ANALYSIS OF EFFECTS OF SO_2 EMISSION STANDARDS ON COAL RESOURCES IN THE EASTERN KENTUCKY COAL FIELD

Frequency distributions for potential sulfur dioxide emissions were constructed for each of 11 principal coal beds in eastern Kentucky (*see* Appendix in Cobb and others, 1982). The tonnage estimates for each coal bed in tons of original resources were apportioned by their potential emissions frequency distributions. Composite frequency and cumulative frequency distributions of resources in terms of potential SO_2 emissions were then constructed (Figs. 1-2) .

A search was made to find a probability model to represent the composite cumulative frequency distribution. The search was restricted to only those probability models that possess a closed-form cumulative distribution function (c.d.f.). Initial attempts were made to fit the following models to the data:

(a) Exponential distribution.

$$\text{c.d.f.}: \quad F(x) = 1 - e^{-\alpha x}, \quad 0 < x < \infty, \quad \alpha > 0.$$

(b) Weibull distribution,

$$\text{c.d.f.}: \quad F(x) = 1 - e^{-\alpha x^{\beta}}, \quad 0 < x < \infty, \quad \alpha > 0, \; \beta > 0.$$

The fit of these distribution functions yielded reasonably small residuals. Plotting these natural distribution functions against the composite cumulative data shows that the lower end of the model, which has the greatest relevance to the EPA standard of 1.2 pounds of SO_2 per million Btu and lower, has not been estimated well enough. Therefore, a mixture of the above distributions was fit to the composite cumulative data. The following models were used:

(c) Mixture of two exponential distributions.

$$\text{c.d.f.}: \quad F(x) = \varrho(1 - e^{-\alpha_1 x}) + (1-\varrho)(1 - e^{-\alpha_2 x}), \quad 0 < x < \infty, \quad \alpha_1 > 0, \quad \alpha_2 > 0, \quad 0 < \varrho < 1.$$

(d) Mixture of two Weibull distributions.

$$\text{c.d.f.}: \quad F(x) = \varrho(1 - e^{-\alpha_1 x^{\beta_1}}) + (1-\varrho)(1 - e^{-\alpha_2 x^{\beta_2}}), \quad 0 < x < \infty, \quad \alpha_1 > 0, \quad \alpha_2 > 0,$$
$$\beta_1 > 0, \; \beta_2 > 0, \; 0 < \varrho < 1.$$

(e) Mixture of exponential and Wiebull distributions.

$$\text{c.d.f.}: \quad F(x) = \varrho(1 - e^{-\alpha_1 x^{\beta_1}}) + (1-\varrho)(1 - e^{\alpha_2 x^{\beta_2}}), \quad 0 < x < \infty, \quad \alpha_1 > 0, \quad \alpha_2 > 0,$$
$$\beta_1 > 0, \; \beta_2 > 0, \; 0 < \varrho < 1.$$

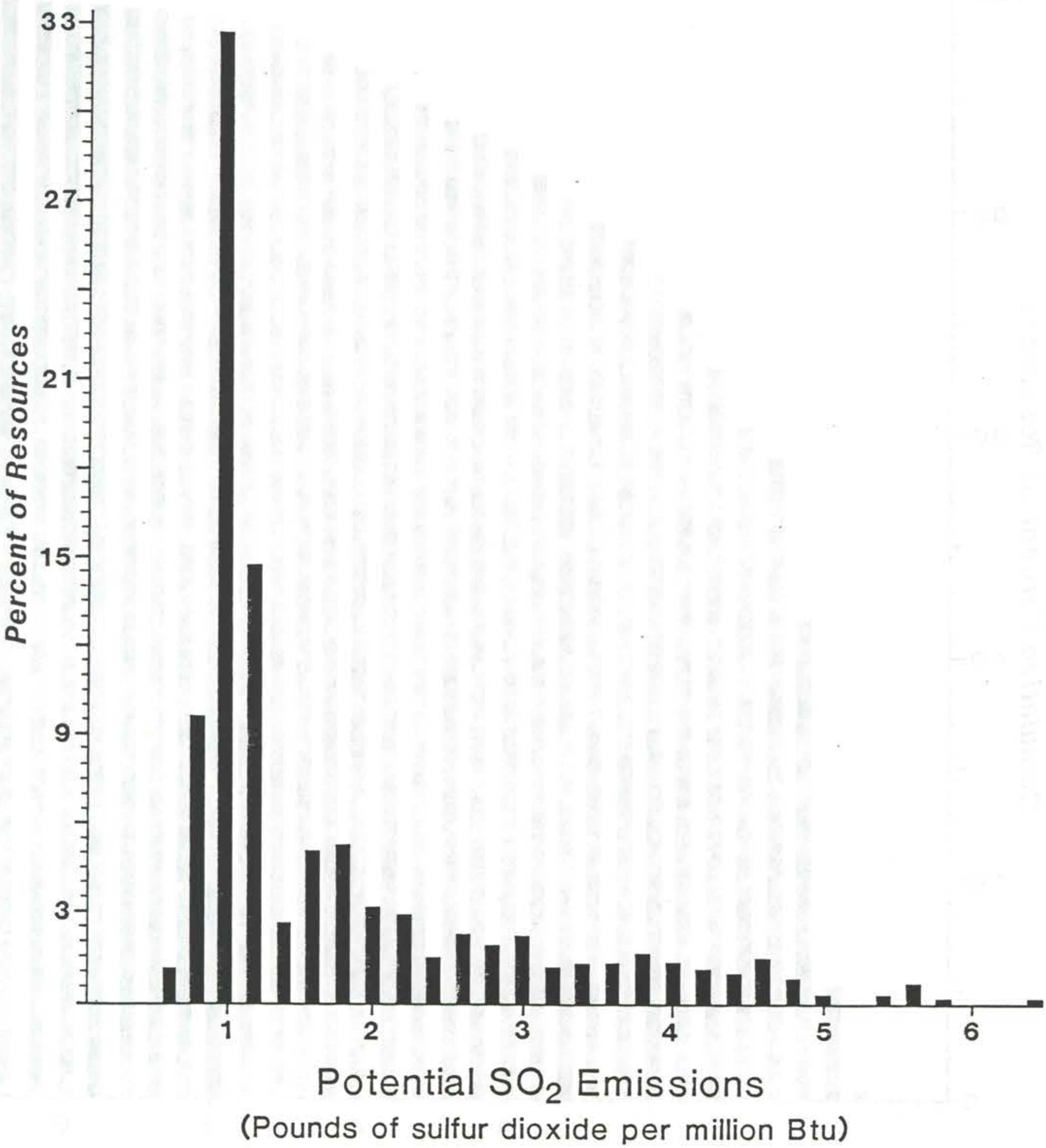

Figure 1. Histogram of potential sulfur dioxide emissions for eastern Kentucky coal resources.

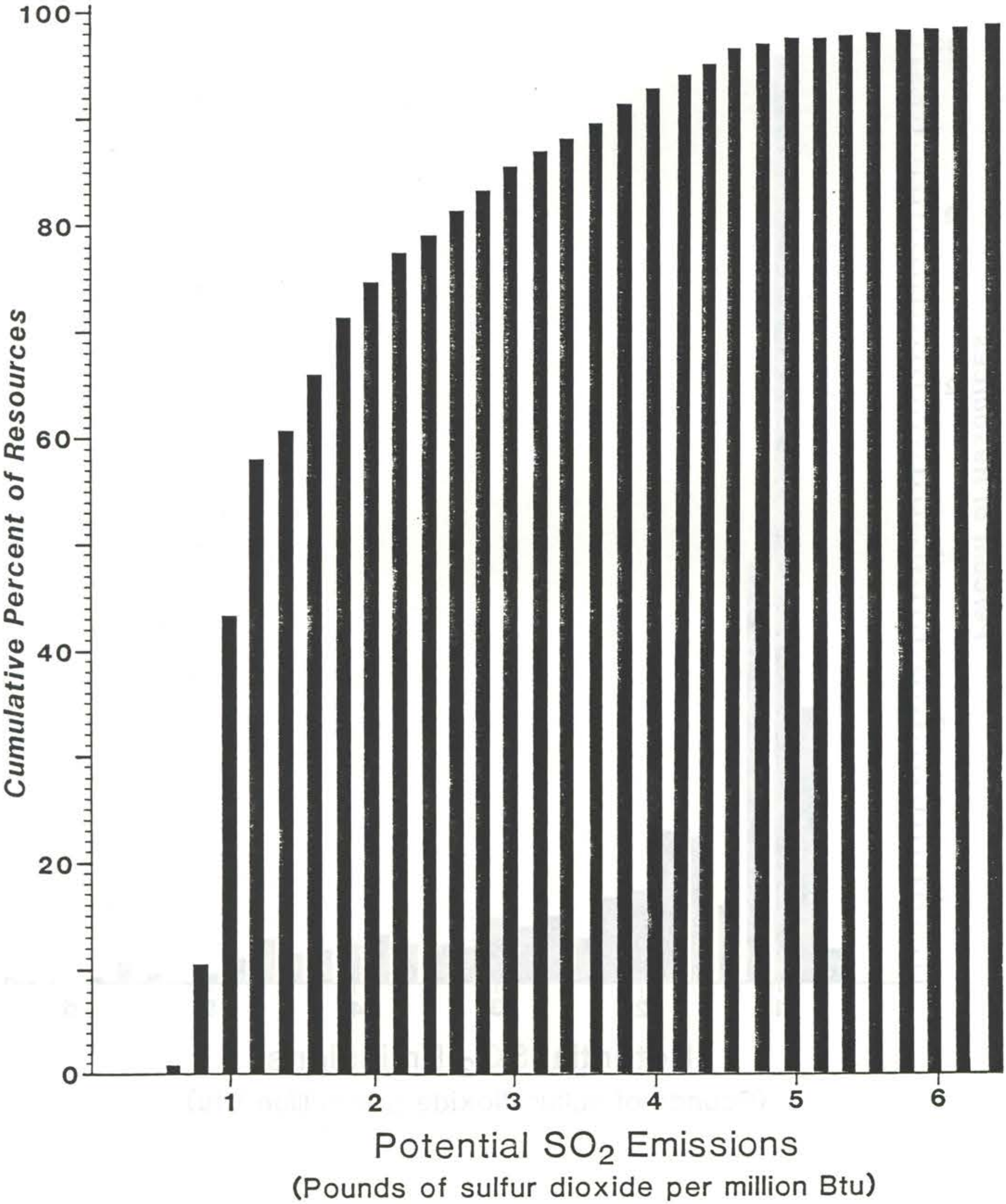

Figure 2. Histogram of cumulative potential sulfur dioxide emissions for eastern Kentucky coal resources.

The ϱ in these cumulative distribution functions represents the mixture proportion of the component functions. Using the notation C to be "is contained in," the following are true of the models (a) through (e):

Model (a) C Model (b) C Model (e) C Model (d);

Model (a) C Model (c) C Model (d). Thus, model (d) is the largest model here.

The resulting mixtures of these models show an extremely good fit to the composite cumulative data. A plot of this model (d) versus the data is shown in Figure 3. The excellent fit of this model to the data indicates its ability to predict potential impacts on resources caused by changes in the compliance standard. The mathematical expression for the cumulative distribution function represented by model (d) is:

$$F(x) = .416(1 - e^{-.235(x-.5)^{1.675}}) + .584(1 - e^{-3.795(x-.5)^{2.402}}),$$

where x is any given potential sulfur emission in pounds of SO_2 per million Btu and F(x) is the percentage of eastern Kentucky resources occurring below that potential sulfur emission.

The cumulative distribution function for SO_2 emissions from western Kentucky resources is shown in Figure 4. This curve differs in form and position on the horizontal axis from the cumulative distribution function for eastern Kentucky resources. Since the curve approaches zero resources near 3 pounds of SO_2 per million Btu, no further analysis of this curve was warranted, but a comparison of Figures 3 and 4 demonstrates the different sulfur contents that characterize these two major coal-producing areas in Kentucky. A comparison of the amounts of resources contained in eastern and western Kentucky can be made from recent resource studies that show nearly 38 billion tons of remaining coal in western Kentucky and 58 billion tons of remaining coal in eastern Kentucky. It should be emphasized that economically mineable coal is only a small fraction of the remaining resources. Further studies must be done to determine the percentage of remaining resources that can be mined economically.

CONCLUSIONS

A cumulative distribution function was derived from exponential and Weibull functions in order to characterize the resources of eastern Kentucky in terms of potential sulfur emissions. This cumulative distribution function is based on coal-quality and coal-resources data from 11 coal beds representing more than 75 percent of the total resources in eastern Kentucky.

The purpose of this probability model is to predict the percentage of eastern Kentucky coal resources affected by changes in the EPA compliance standard. The EPA compliance standard is currently 1.2 pounds of SO_2 per million Btu for most operating power plants. The probability model predicts that approximately 50 percent of the resources in eastern Kentucky are in compliance at this standard. The current standard for most new power plants is 0.6 pound of SO_2 per million Btu. Only 1 percent of eastern Kentucky resources is estimated by the model to be in compliance at this standard without extraordinary coal cleaning and processing.

Figure 5 gives the mathematical equation for the cumulative distribution model. This equation can be solved when values for any proposed emission standard are inserted into it. When the equation is solved, the percentage of resources in compliance (F(x)) with the given SO_2 standard (x) is obtained.

Table 1 shows calculated solutions for this equation using emission standards (x) of 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, and 0.6 pounds of SO_2 per million Btu. The calculated percentage of resources in compliance varies from 51 percent at 1.2 pounds of SO_2 per million Btu down to only 1 percent at 0.6 pounds of SO_2 per million Btu. In the range of possible SO_2 emission standards from 1.2 to 0.6, each change of 0.1 pound of SO_2 per million Btu causes an extremely large percent change in the available resources.

In addition to the limiting influence of governmental regulation on coal resources, the adverse effects of geological impediments must also be considered. The term *resources* as used in this investigations includes *all* of the

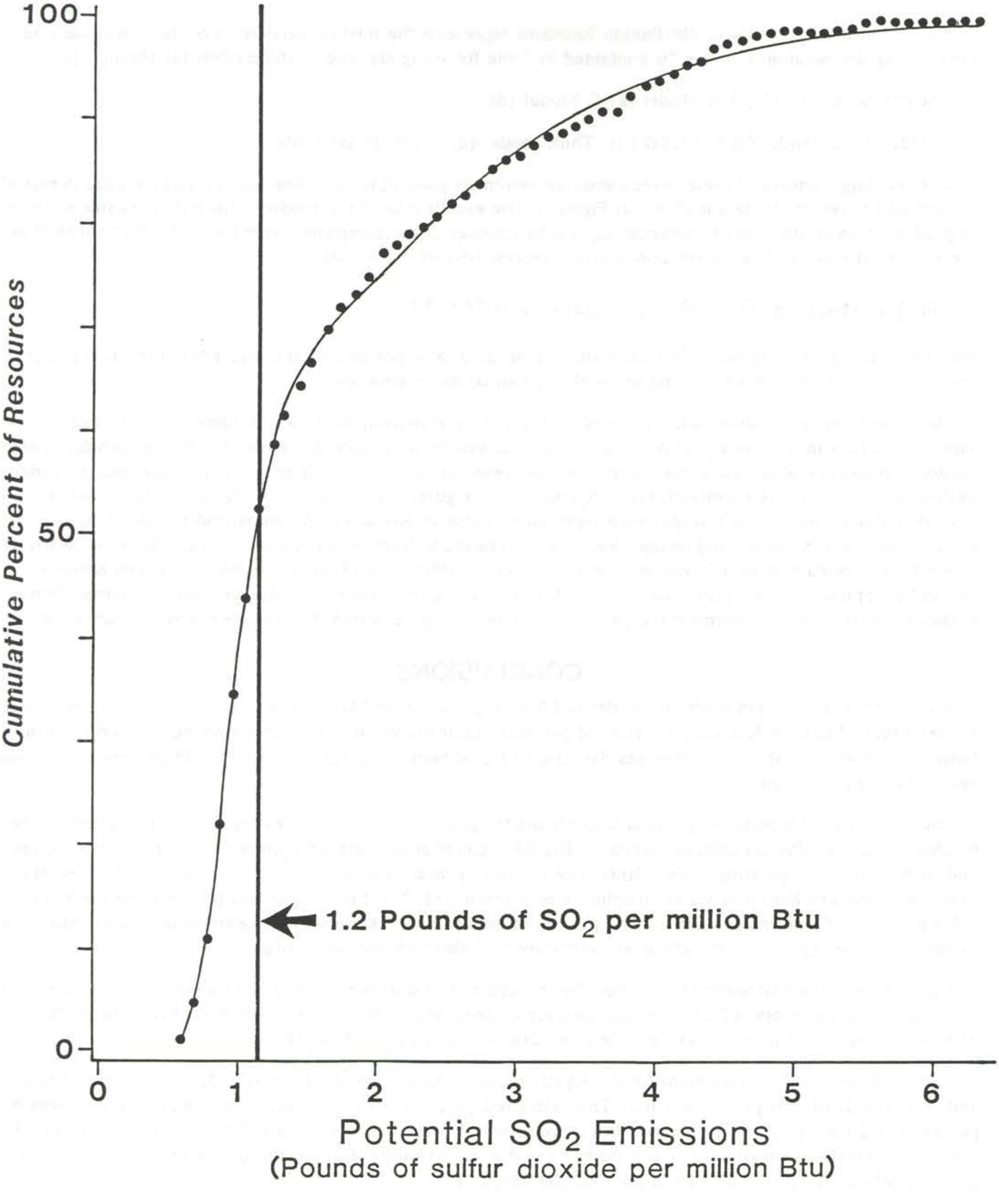

Figure 3. Theoretical cumulative distribution function of potential sulfur dioxide emissions for eastern Kentucky coal resources. Circles show actual values.

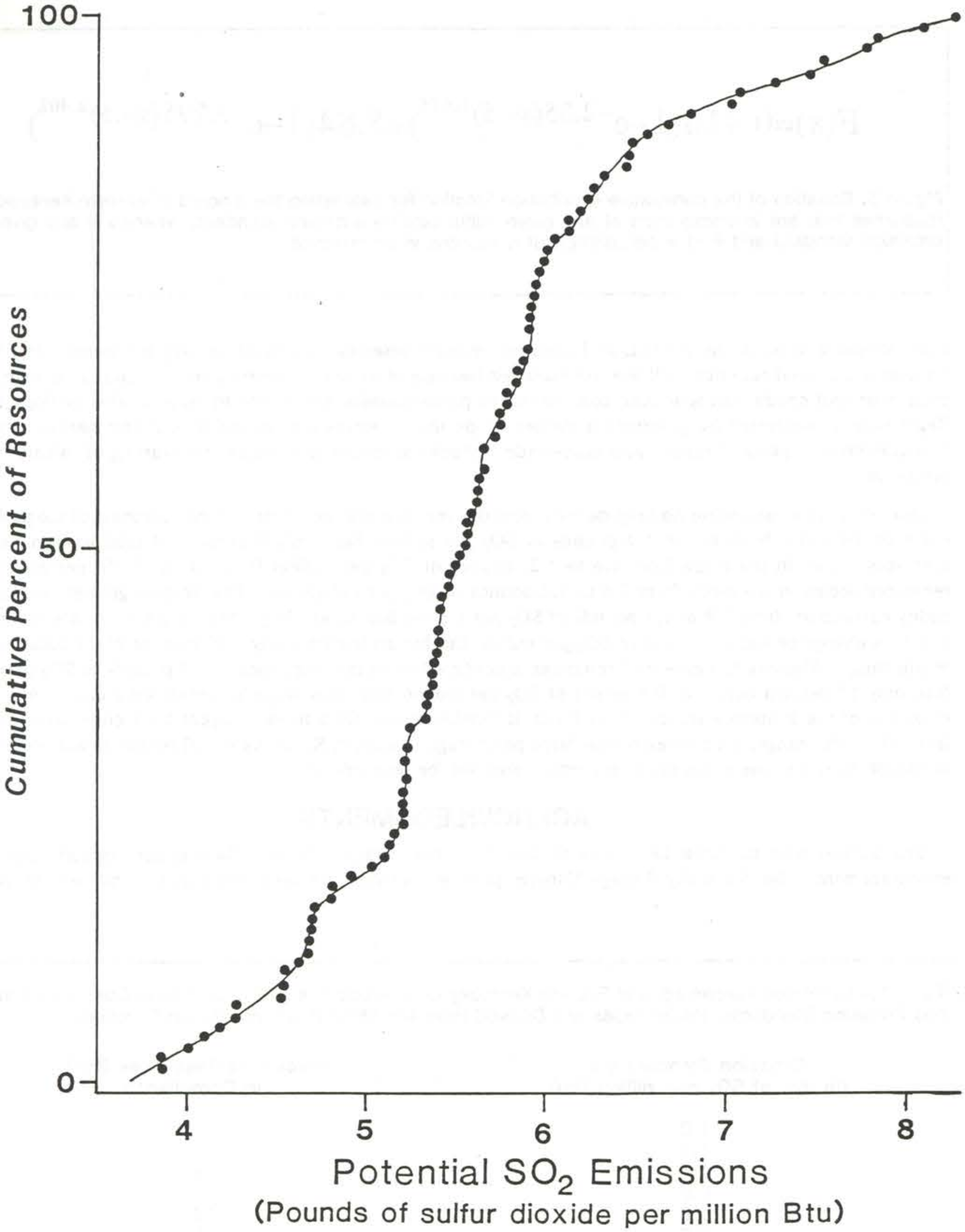

Figure 4. Cumulative distribution function of potential sulfur dioxide emissions for western Kentucky coal resources.

$$F(x)=0.416(1-e^{-2.35(x-.5)^{1.675}})+5.84(1-e^{-3.795(x-.5)^{2.402}})$$

Figure 5. Equation of the cumulative distribution function for estimating the amount of eastern Kentucky coal resources that are in compliance at any given sulfur dioxide emission standard, where x = any given SO_2 emission standard and F(x) = percentage of resources in compliance.

coal estimated to be in the ground, and does not indicate reserves that could actually be mined. Only a small fraction of the total resources will ever be extracted because of naturally occurring barriers to mining such as thin coal; poor roof conditions; split coal; coal cut out by paleochannels, faults, and folds; and other geologic factors. Regulations promulgated by government further divide the resources into mineable and unmineable categories. The combined impacts of natural and man-made obstacles to mining may lead to the wasting of valuable natural resources.

One of the most important findings derived from this model is the recognition of the steepness of the probability curve in the range from 0.6 to 1.2 pounds of SO_2 per million Btu. Only 9 percent of total eastern Kentucky resources occurs in the range from 1.6 to 1.2. pounds of SO_2 per million Btu, but nearly 50 percent of these resources occurs in the range from 0.6 to 1.2 pounds of SO_2 per million Btu. The steepest gradient of this probability curve exists from 0.8 to 1.1 pounds of SO_2 per million Btu, where 31 percent of resources are estimated to occur. A change of just 0.1 pound of SO_2 per million Btu has an impact on over 10 percent of the total resources in this range. Whereas 43 percent of resources is predicted to be in compliance at 1.1 pounds of SO_2 per million Btu, only 12 percent occurs at 0.8 pound of SO_2 per million Btu. This range is considered a crucial one for the resources of the Eastern Kentucky Coal Field. If legislation dictates a more stringent EPA compliance standard that falls in this range, then an extremely large percentage of eastern Kentucky's coal resources will no longer be in compliance, and the economy of the entire area will be jeopardized.

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Table 1.—Estimated Percentages of Eastern Kentucky Coal Resources That Would be in Compliance at Various Emission Standards. Percentages are Derived from the Theoretical Distribution Function.

Emission Standard (x) (in lbs. of SO_2 per million Btu)	Percent of Resources (F(x)) in Compliance
1.2	51
1.1	43
1.0	32
0.9	22
0.8	12
0.7	5
0.6	1

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