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The RAMS Coal Model
Volume I – Model Overview

David B. Reister
Jeffrey V. Conopask
Philip E. Mihlmester

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Engineering Physics and Mathematics Division

THE RAMS COAL MODEL

VOLUME I - MODEL OVERVIEW

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ABSTRACT

The RAMS coal model was developed to aid the planning functions of the Office of Fossil Energy of the Department of Energy. The model was designed to simulate the market penetration of processes that use coal to produce liquid fuels. To simulate market penetration, we assume that the least cost process will have the largest share of the market. To evaluate the future income and costs for a process, we need to estimate the prices of all of the inputs and outputs for all of the coal processes and for all of the competing processes. After a literature review, we identified 26 types of energy, by-products, and factors of production that are potential inputs or outputs for a process. The coal model simulates the supply and demand for the 26 types of goods.

The coal model input-output (I-O) structure has 13 sectors to produce the first 24 goods (the last 2 factors, labor and capital, are exogenous inputs). The first 10 sectors produce the first 10 goods, which are either primary or secondary forms of energy. Sector 11, the liquid fuels sector, produces refined petroleum products and by-products, the goods from 11 to 23. Sector 12 produces good 24, materials. The final sector, sector 13, is the trade sector.

This report provides an overview of the RAMS coal model. After an introduction to the RAMS family of models, we discuss some of the key design issues for the coal model. To demonstrate the flexibility of the model, we adjusted the parameters and input variables of the model in an attempt to reproduce the base case scenario published in the most recent National Energy Policy Plan (NEPP). The results demonstrated that the model can create a scenario that is quite similar to the NEPP scenario.

1. INTRODUCTION

This is the first of three volumes of the documentation for the Research and Development Analysis Modeling System (RAMS) coal model. The first volume is an overview of the model and its results. The second volume is a user's guide, that discusses the input and output data sets for the model. The third volume will provide an introduction to the methodology used to construct the algorithms used by the model.

The RAMS coal model is the third in a series of models that are being developed for the U.S. Department of Energy, Office of Fossil Energy. The first model, RAMSOIL, simulates the penetration of synthetic and unconventional oil into world markets.[1] The second model, RAMSGAS, simulates the penetration of synthetic and unconventional gas into world markets.[2] The RAMS Coal model simulates the penetration of secondary types of energy (clean coal, electricity, and liquid and gaseous fuels) produced from coal into the United States market. RAMSOIL and RAMSGAS simulated the supply and demand for a single form of energy in several regions. The RAMS Coal model simulates the supply and demand for many forms of energy in a single region; imports and exports of energy are simulated by the trade components of the model.

The RAMS family of models is designed to aid the planning functions of the Office of Fossil Energy. The Office of Fossil Energy is supporting R&D to develop unconventional technologies that produce clean energy from fossil fuels. Over time the conventional sources of crude oil and natural gas will be depleted and the unconventional technologies will penetrate the market. The DOE staff must plan their R&D program so that the unconventional technologies are technically ready when the market wants them.

In the last two decades, many reports have been written and many models have been developed to forecast the future of energy markets. Despite these efforts, the world energy markets have been repeatedly buffeted by surprises and shocks. Since the large models are unable to forecast the future of energy markets, the DOE planners have supported the development of the RAMS models.

The RAMS models are intended to be used to analyze long-term trends in energy supply and demand. They are intended to be flexible models that can be used to easily create a wide variety of alternative scenarios. They have a long-term planning horizon (1985-2030) to simulate the future transition from conventional to unconventional fuels. They run on IBM-PC compatible micro-computers and are user-friendly. The models are robust and can tolerate a wide range of values for the input parameters. The development of fast compact models requires a disciplined approach that identifies and simulates the essential features of the energy markets.

RAMSOIL and RAMSGAS were written in LOTUS 1-2-3 to make the key model assumptions and parameters visible to the user. Since a LOTUS version of the coal model would be too large to run on an IBM-PC, the coal model is a hybrid model. LOTUS can be used to allow the user to easily change key parameters; and TURBO Pascal has been used to perform the calculations of the model.

The coal market is complex. There are hundreds of types of coal, each with different properties. Coal can be used directly or can be converted to a secondary form of energy before final use. To be used, coal must be mined, cleaned, transported, converted, and consumed.

The focus of the RAMS coal model is on the market penetration of processes that use coal to produce liquid fuels. Although most coal is

used to make electricity, the DOE office that supported the development of the coal model was planning R&D on processes that produce liquid fuels from coal. If the model had been focused on the pathway from coal to electricity, the design of the model would have had more emphasis on the emissions of sulfur and nitrogen oxides.

Liquids can be produced from coal either directly or indirectly. In the indirect process, a synthesis gas is produced from coal and liquid fuels are produced from the synthesis gas. The two indirect processes that have experienced the most development are the Fischer-Tropsch process and the Mobil methanol-to-gasoline process. The outputs from the Fischer-Tropsch process include gasoline, diesel fuel, fuel oil, and alcohols. The Mobil process produces gasoline.

The direct process produces liquid fuels from coal without going through the gasification stage. The two direct processes that have experienced the most development are H-Coal and EDS. Both processes produce a broad spectrum of hydrocarbon liquids ranging from heavy fuel oil to gasoline to LPG.

Both the direct and indirect processes produce valuable by-products. The by-products include methane, sulfur, ammonia, and carbon dioxide. In a recent ORNL study of the process economics of methanol from coal,[3] the sale of carbon dioxide reduced the cost of methanol by $1.00 per million BTU.

To design a model of the market for processes that produce liquid fuels from coal, we must identify all of the inputs, outputs, by-products, and competitors for the processes. Consider coal types. In a recent study of the economics of the EDS process,[4] the following types of coal were analyzed:

1. Bituminous - Illinois (No. 6, Monterey Mine)
2. Bituminous - West Virginia (Pittsburgh No. 8, Ireland Mine)
3. Subbituminous - Wyoming (Wyodak Mine)
4. Subbituminous - Queensland (Wandoan, Austinvale Mine)
5. Lignite - Texas (Martin Lake Mine)

The five types of coal were identified by rank, region, and mine.

For each good or service we choose to model, we must identify all of the sources of supply and demand. We quickly decided not to model each coal mine or each coal producing region as a separate good. We planned to define coal types by rank and sulfur content. However, we were financially unable to develop the data base. Thus, we chose to model coal by rank: bituminous, subbituminous, lignite, and metallurgical.

Currently, liquid fuels are produced from crude oil in the petroleum refining sector. In the future, conventional crude oil will be depleted and unconventional processes (coal, oil shale, tar sands, or heavy oil) will produce the liquid fuels. The petroleum refining sector provides a context for the market penetration of processes that produce liquid fuels from coal.

Petroleum refineries produce a broad spectrum of products. The Petroleum Supply Annual[5] tabulates 22 types of refined products. By combining categories, we defined 9 types of refined products.

After an analysis of all of the potential inputs and outputs for the coal processes or their competitors, we identified 26 types of goods and services. Our list of 26 types of energy, by-products, and factors of production is displayed in Table 1. Many economic models have capital, labor, energy, and materials as factors of production. We have expanded the smallest factor (energy) into 23 types of energy and by-products.

Table 1. The Base Year Values for the Factors of Production in the Coal Model.

The physical units are given in the table.
The price units are billion $1985 per physical unit.
The value units are billion 1985 dollars.

	Factor	Quantity	Units	Price	Value
1	Coal 1 - Bituminous	0.57	Billion Tons	41.31	23.68
2	Coal 2 - Subbituminous	0.19	Billion Tons	27.86	5.19
3	Coal 3 - Lignite	0.07	Billion Tons	12.67	0.88
4	Coal 4 - Metallurgical	0.08	Billion Tons	58.50	4.73
5	Crude Oil	4.40	Billion Barrels	26.76	117.83
6	Dry Natural Gas	17.28	Trillion Cu Ft	2.51	43.38
7	Transported Gas	16.31	Trillion Cu Ft	3.81	62.16
8	Distributed Gas	6.87	Trillion Cu Ft	5.90	40.51
9	Bulk Electricity	2.54	Billion MWH	50.47	127.99
10	Distributed Electricity	1.43	Billion MWH	73.72	105.46
11	Liquid Petroleum Gases	1.30	Billion Barrels	23.50	30.55
12	Gasoline	2.50	Billion Barrels	36.48	91.32
13	Kerosene	0.49	Billion Barrels	36.50	17.75
14	Distillate Fuel Oil	1.05	Billion Barrels	31.96	33.46
15	Residual Fuel Oil	0.44	Billion Barrels	24.40	10.71
16	Naphthas	0.16	Billion Barrels	33.00	5.35
17	Lubricants	0.06	Billion Barrels	33.00	1.96
18	Petroleum Coke	0.16	Billion Barrels	33.00	5.44
19	Asphalt	0.16	Billion Barrels	33.00	5.12
20	Alcohol	0.02	Billion Barrels	22.68	0.48
21	Sulfur	0.01	Billion Tons	65.00	0.74
22	Ammonia	0.02	Billion Tons	125.50	2.03
23	Carbon Dioxide	0.07	Trillion Cu Ft	1.00	0.07
24	Materials	4396.05	Billion 1985$	1.00	4396.05
25	Labor	2529.13	Billion 1985$	1.00	2529.13
26	Capital	1468.97	Billion 1985$	1.00	1468.97

The model has three types of natural gas. Natural gas wells produce both dry natural gas and LPG. The gas pipeline industry buys dry natural gas at the wellhead and provides transported gas to the electric utilities, the industrial sector, and to the gas distribution companies. The gas distribution companies buy transported gas and sell distributed gas to the residential, commercial, and transportation sectors. By having three types of gas, we can have three distinct prices for natural gas.

The model has two types of electricity. Bulk electricity is sold to the industrial sector and to the electricity distributors. Distributed electricity is sold to the residential, commercial, and transportation sectors.

We define "Materials" to be all of the goods and services that are produced by the economy except for the 23 types of energy and by-products. The inputs to the economy are labor and capital, while the outputs are materials and the 23 types of energy and by-products.

We assume that the prices of labor and capital are exogenous and that the prices of the first 24 goods in Table 1 are determined by the interaction of supply and demand. To trace the supply and demand for the 24 goods, we will use an Input-Output (I-O) accounting framework. The most recent and detailed I-O table for the United States has 537 sectors. For the coal model I-O structure, we collapse most of the 537 types of goods and services into our materials sector and disaggregate the energy sectors. For example, the detailed table has one sector for the production of both crude oil and natural gas while the coal model has one sector for crude oil and another sector for the production of dry natural gas and LPG.

The coal model I-O structure has 13 sectors to produce the first 24 goods in Table 1. The first 10 sectors produce the first 10 goods in Table 1. Sector 11, the liquid fuels sector, produces the goods from 11 to 23 in Table 1 (LPG is both an input to and an output from the liquid fuels sector). Sector 12 produces materials. The final sector, sector 13, is the trade sector.

The coal model was designed to simulate the market penetration of processes that use coal to produce liquid fuels. The liquid fuels sector is the key sector in the model. Initially, all liquid fuels are produced

from crude oil and the liquid fuels sector is the combination of the petroleum refining industry and the industries that produce the by-products. Over time, unconventional liquid fuels from coal, oil shale, tar sands, or heavy oil will gradually penetrate into the liquid fuels sector.

The inputs to the materials sector are capital, labor, materials, and 19 of the 23 types of energy and by-products (the types of energy that are not inputs are subbituminous coal, lignite, crude oil, and dry natural gas). The inputs to the trade sector are the exports of goods and services, while the outputs are the imports.

The first 11 sectors are the energy supply side of the economy and the materials sector is the energy demand side of the economy. In each year, the energy supply is fixed while the demand is responsive to price. The price is determined by requiring that supply and demand balance for each of the goods.

To increase the speed of the calculation and to reduce the complexity of the data base, the I-O structure of the model has been simplified. For example, in the 537 sector I-O table, the coal sector has inputs from labor, capital, and 127 other sectors. In the coal model, the single coal sector in the 537 sector table has been split into 4 sectors, but each of the 4 coal sectors has a single input - materials. The simplification of the I-O structure corresponds to the assumption that all coal is produced by a coal service company.

In the coal model, all labor and capital are used to produce materials. The inputs to the energy sectors are energy and materials. Materials are consumed by the energy sectors, by the materials sector, and

by final demand (GNP). Expensive energy requires more materials and reduces the GNP.

The overall architecture of RAMSCOAL is illustrated in Fig. 1. The core of the model is a general equilibrium model of the supply and demand for the 23 types of energy and by-products (see Table 1). Given input and output (I-O) coefficients for each of the first 12 sectors and the levels of imports and exports, the core model can balance supply and demand and forecast prices and quantity of production for the 23 types of energy and by-products. The I-O coefficients for each sector can be forecast by a family of satellite models.

The design of the coal model has allowed a staged development. In the first phase, the core model, the satellite model for the liquid fuels sector, and the supply models for coal, oil, and gas were developed. In the second phase, international trade was added and a satellite model was developed for the end-use demand for coal and other forms of energy. In the future, satellite models could be developed for the production of electricity, clean coal, and high BTU gas.

For a financial analysis of H-Coal process,[6] the Pace Company used five types of models:

1. Econometric Model - A commercially available, large scale, fully integrated model of the United States economy.
2. Sector Demand Models - The sector demand models use inputs of energy prices and economic activity from the econometric model and forecast energy consumption by fuel type and region.
3. Petrochemical Model - Using inputs from the econometric model, the model forecasts demand for petrochemicals.

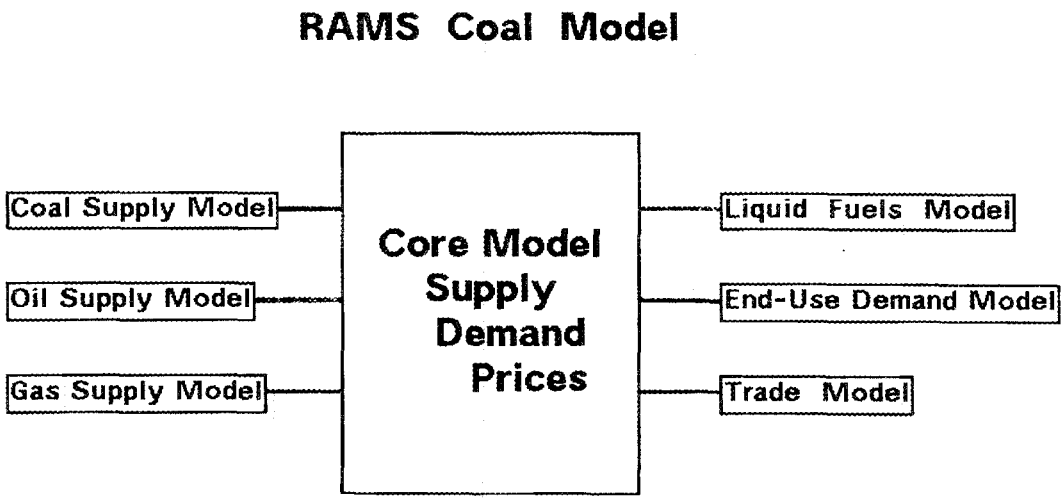

Fig. 1. The Structure of the RAMS Coal Model.

4. Refinery Model - A generalized LP model to forecast the optimum slate of fuel products and petrochemicals.
5. Pricing Model - Given the prices of crude oil and natural gas, the model forecasts the prices of refined products and petrochemicals.

The RAMS coal model is a compact version of the five types of models used by Pace.

For the economic analysis of the EDS process reported in Ref. 4, the Process Alternatives LP Model (PAM) was used to calculate the Required Initial Selling Price (RISP) for each process option. For the economic analysis of the production of methanol from coal reported in Ref. 3, the PRP model was used to perform a Discounted Cash Flow (DCF) analysis of the process options.

The Pace models and PAM are proprietary models that could not be reviewed for this project. The PRP model was available and was carefully studied before the DCF section of the coal model was developed. As described in Volume 3, two versions of the DCF model were developed: long and short. The long version is similar to PRP. The short version gives the same results as the long version; however, analytical formulas are used to speed the calculation.

Reports are not as satisfactory as models for R&D planning. Comparing a set of reports is difficult, unless the reports use the same assumptions. If a planner wishes to analyze the impact of a change in assumptions, reports are not as helpful as models. The RAMS coal model provides a "level playing field" for the analysis of process options. All of the options are described in the same format and compete under a common set of assumptions.

The RAMS coal model can identify "windows of opportunity." For a typical analysis, a single set of price assumptions is used. In the coal model, the DCF analysis is repeated for every year from 1985 to 2030. As the relative prices evolve, the planner can identify "windows" where a process option will begin to penetrate the market.

This report will conclude with some results from the RAMS coal model. The model can be used to model the market penetration of processes that produce liquid fuels from coal. In Volume 2, we will discuss the detailed inputs and outputs for the model. The model forecasts 76 different variables. With so much detailed output, the overall results of the model are not easy to identify. We will focus on overall results in this report.

2. MODEL RESULTS

Periodically, the DOE publishes a National Energy Policy Plan (NEPP). The most recent NEPP was published in 1985.[7] To demonstrate the flexibility of the RAMS coal model, we have adjusted the parameters and input variables and attempted to reproduce the NEPP results. The primary input variables for the RAMS coal model are the world oil price and the level of economic output. Values for these variables were obtained from the NEPP report and are displayed in Table 2 of Volume 2.

To compare the results of the coal model with NEPP, we prepared the summary report Energy.Out (see Table 2). The summary report displays primary energy consumption by energy type (oil, gas, coal, other, and total) for the period from 1985 to 2030.

Table 2. The Output Data Set Energy.Out.

Primary Domestic Energy Consumption Summary.
The Units are Quadrillion BTU and Billion MWH for Electricity.

Year	Oil	Gas	Coal	Other	Total	Electric
1985	30.920	17.849	17.480	7.710	73.960	2.536
1990	37.100	20.604	21.526	9.522	88.752	3.132
1995	36.821	21.501	24.191	10.629	93.141	3.496
2000	36.083	21.807	27.385	11.847	97.121	3.897
2005	34.343	21.452	31.301	13.200	100.296	4.342
2010	32.538	20.495	36.545	14.774	104.352	4.860
2015	31.526	18.616	42.154	16.299	108.595	5.361
2020	31.220	16.908	47.981	17.886	113.995	5.883
2025	31.033	16.484	53.685	19.531	120.734	6.424
2030	30.851	16.865	58.473	21.027	127.217	6.916

To create Table 2, we needed to define the amount of primary energy associated with each of the variables in the coal model. For the primary

energy associated with oil, we added the domestic production and imports of crude oil and LPG. We found that our base year estimate was smaller than the value for 1985 in the **Annual Energy Review (AER)**.[8] We added the energy that was associated with the imports and exports of refined products and we were still 4% smaller than the AER value. We used a multiplicative adjustment factor to match the AER value. For natural gas the adjustment factor was 1.09, while for coal the factor was 0.95.

The NEPP report includes renewable energy (primarily wood) that is used in the residential and industrial sectors. Since this contribution to primary energy is not included in the AER or in the RAMS coal model, we subtracted this renewable energy from the NEPP results. To estimate the contribution of the "Other" category (other is the sum of nuclear energy and renewable energy), we multiplied the electricity production by an adjustment factor.

Estimation of the total consumption of primary energy requires a set of accounting conventions. In addition to the issue of renewable energy in the residential, commercial, and industrial sectors, accounting conventions are required for oil shale, tar sands, heavy oil, and underground coal gasification. To avoid the work of establishing accounting conventions for the unconventional processes in the liquid fuels model, we temporarily removed them from the model by changing the introduction year to 2040 for processes 7 to 11 (see Appendix B of Volume 2). To simulate the introduction of oil shale, tar sands, and heavy oil, we used the two generic processes in the oil supply model.

The NEPP forecast of oil consumption is compared to the RAMS forecast in Fig. 2. For both forecasts, the long-term results are similar; the consumption of oil is almost constant. The greatest difference between the

two forecasts occurs in 1990. Although the NEPP forecast for 1990 will probably be closer to the actual consumption, the reason that the RAMS result is higher than the NEPP result is interesting.

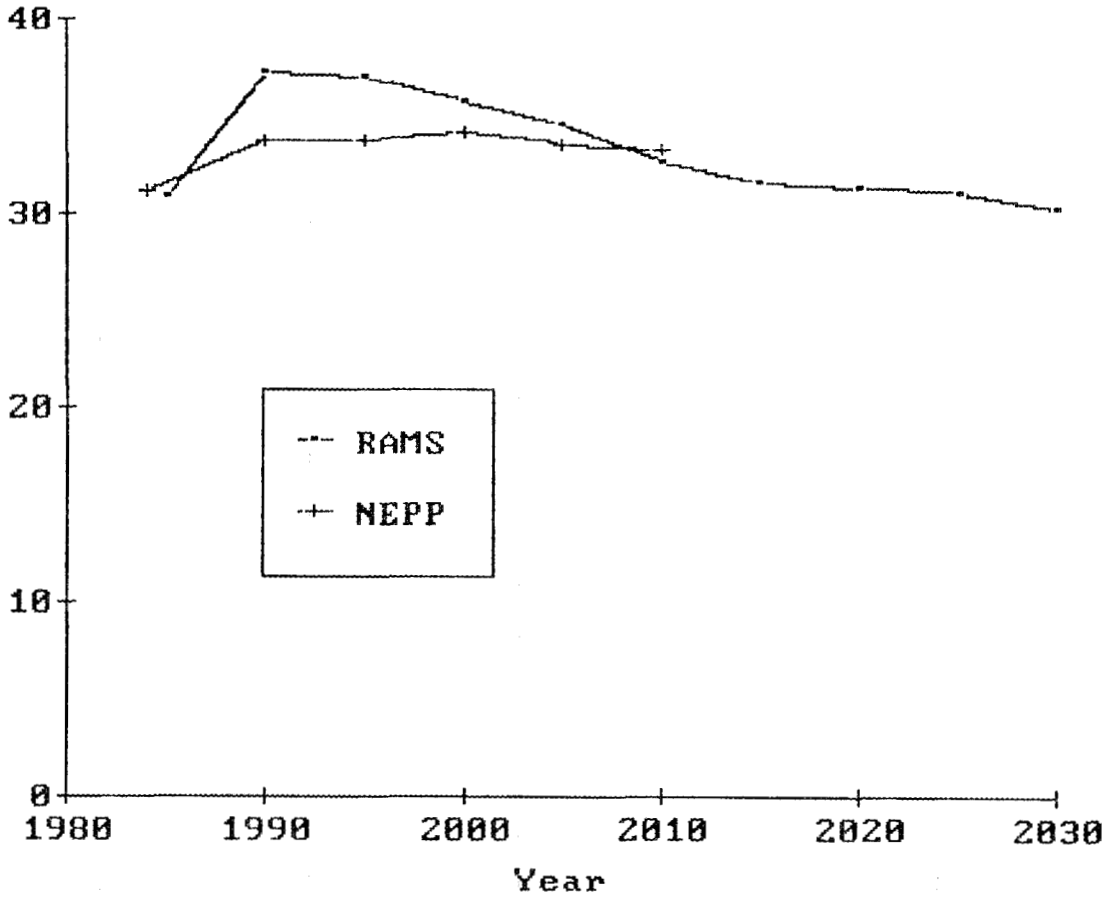

Fig. 2. Comparison of the RAMS Forecast of Oil Consumption with the NEPP Forecast (Quadrillion BTU per Year).

The RAMS coal model uses 1985 as a base year. If there is no change in price, the input-output coefficients for the model will be constant and consumption of oil will increase with the GNP. For the NEPP scenario, the oil price decreases from 1985 to 1990 and the GNP increases by 23%. Thus, the coal model must forecast a large increase in oil demand. To develop a more realistic forecast, we should have a base year that is before the oil price shocks in 1974 and 1979.

We adjusted the parameters in the RAMS model to approximately match the NEPP result in 2010. We adjusted the price elasticity of the oil demand by varying the cb parameters (see Volume 3 and the data set CoalBase.Dat).

The NEPP forecast of gas consumption is compared to the RAMS forecast in Fig. 3. For both forecasts, the long-term results are similar; the consumption of gas is almost constant. The RAMS forecast is always higher than the NEPP forecast. It is higher in 1990 for the same reason as the oil forecast (because 1985 is the base year). It is higher in 2010 because the cb parameters provide limited control of the price elasticity.

The NEPP forecast of coal consumption is compared to the RAMS forecast in Fig. 4. The two forecasts are almost identical. In contrast to the zero growth in demand for oil and gas, both forecasts show a large increase in consumption of coal.

The two forecasts are compared for "other energy" in Fig. 5, for "total energy" in Fig. 6, and for electricity in Fig. 7. For all three cases, the differences between the forecasts are small. For all three cases, there is a large increase in energy consumption.

Figures 2 to 7 demonstrate that the RAMS coal model can create a scenario that is quite similar to the NEPP scenario.

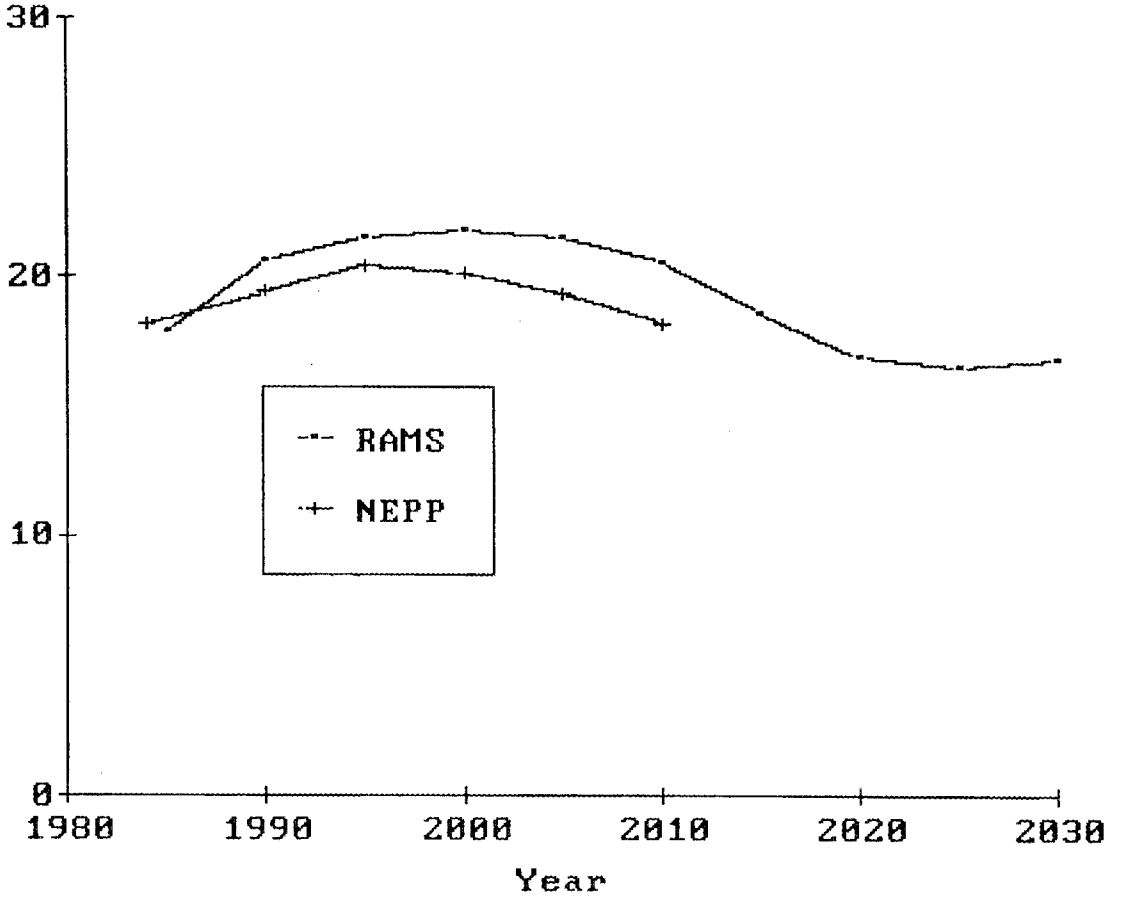

Fig. 3. Comparison of the RAMS Forecast of Gas Consumption with the NEPP Forecast (Quadrillion BTU per Year).

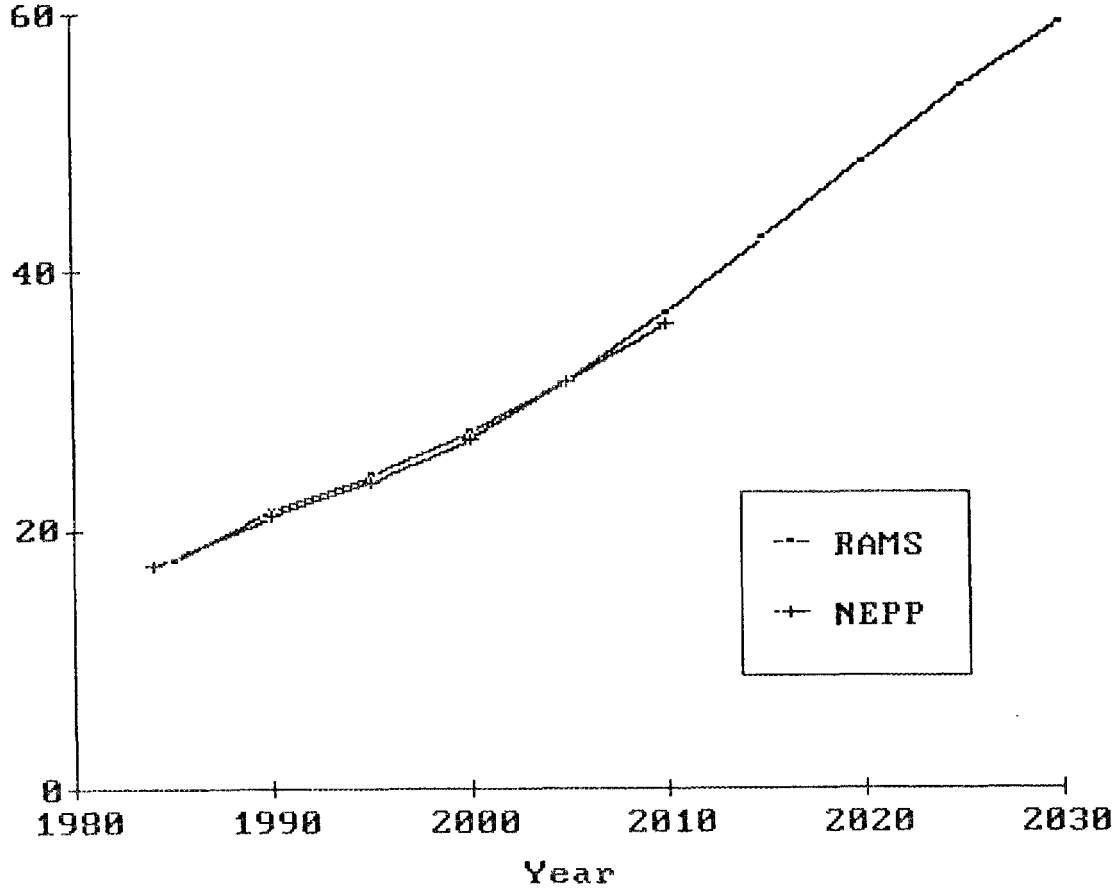

Fig. 4. Comparison of the RAMS Forecast of Coal Consumption with the NEPP Forecast (Quadrillion BTU per Year).

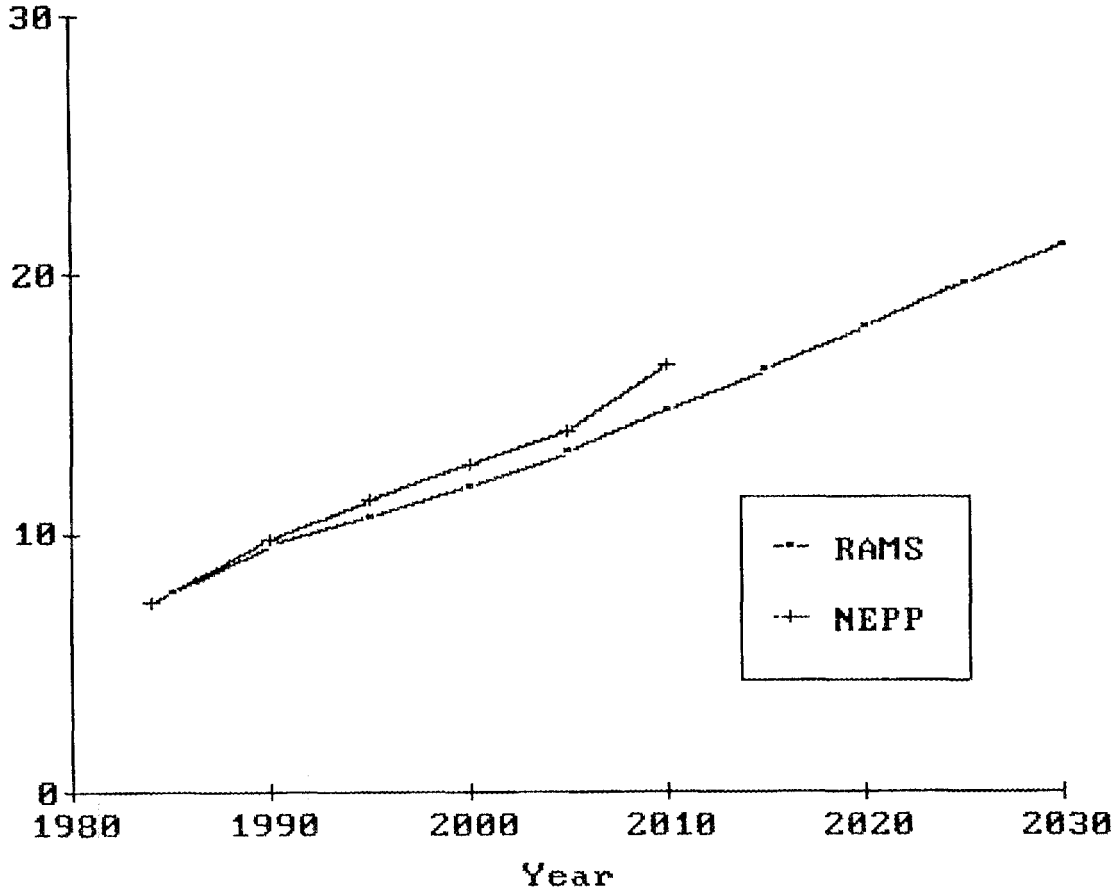

Fig. 5. Comparison of the RAMS Forecast of Other Consumption with the NEPP Forecast (Quadrillion BTU per Year).

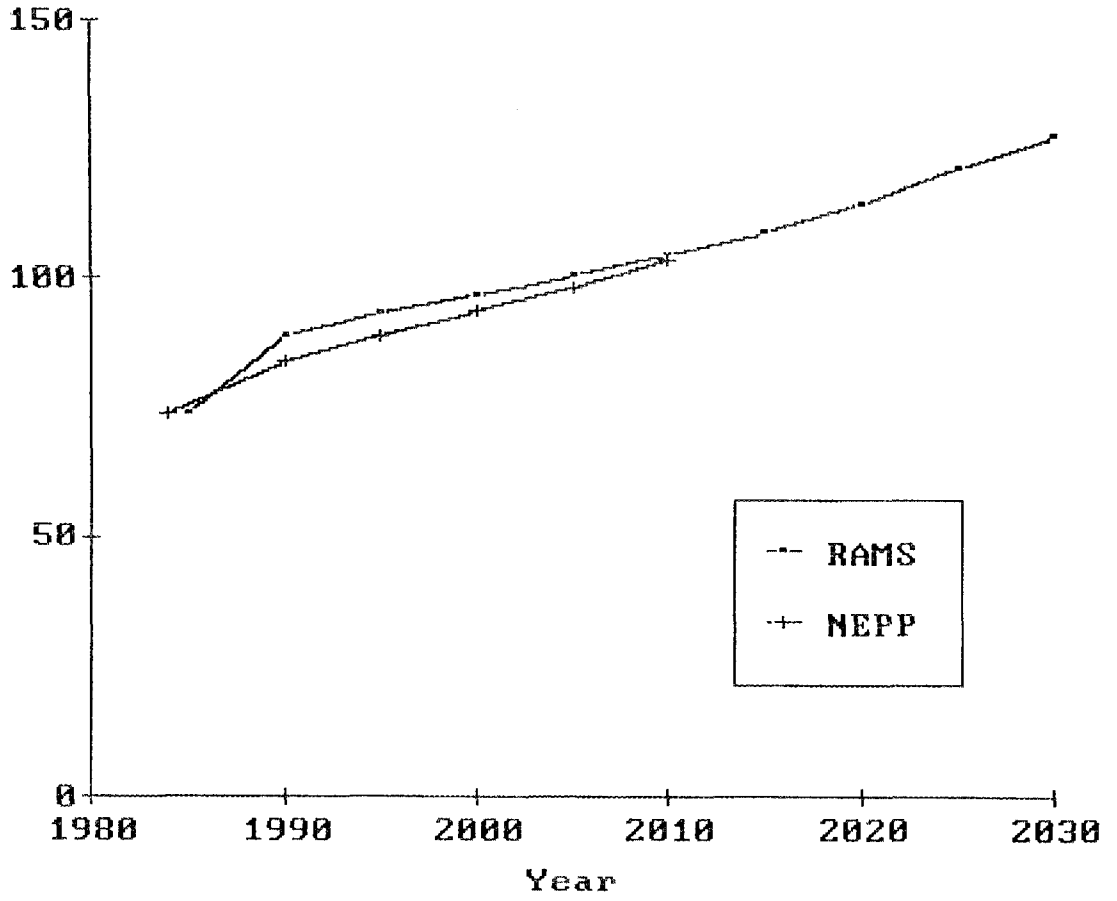

Fig. 6. Comparison of the RAMS Forecast of Total Consumption with the NEPP Forecast (Quadrillion BTU per Year).

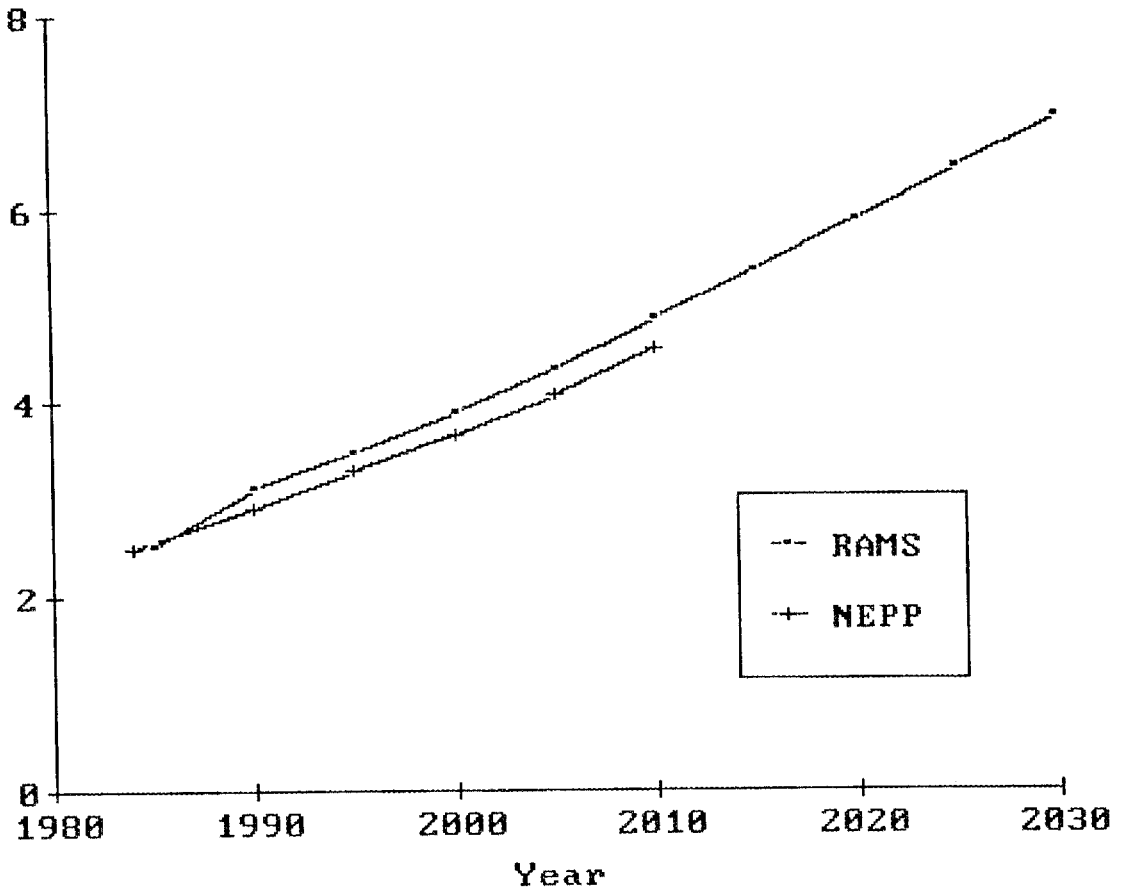

Fig. 7. Comparison of the RAMS Forecast of Electricity Consumption with the NEPP Forecast (Quadrillion BTU per Year).

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