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The RAMS Coal Model
Volume III – Model Description

David B. Reister
Jeffrey V. Conopask
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ORNL/TM-10686/V3

Engineering Physics and Mathematics Division

THE RAMS COAL MODEL

VOLUME III - MODEL DESCRIPTION

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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.

The overall architecture of RAMSCOAL features a core model and a family of satellite models. The core model is a general equilibrium model of the supply and demand for the 23 types of energy and by-products. Given I-O coefficients for each of the first 12 sectors and the levels of imports and exports, the core model balances supply and demand and forecasts prices and quantity of production for the 23 types of energy and by-products. The I-O coefficients for each sector are forecast by the satellite models.

This report presents the equations for the core model and for all of the existing satellite models. The supply models (oil, gas, and coal) calculate the I-O coefficients for the first 6 sectors. The liquid fuels model calculates the coefficients for sector 11. The end-use model calculates the coefficients for sector 12. The remaining sectors (7 to 10) have fixed coefficients.

1. INTRODUCTION

This is the third volume 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 the user's guide. This volume will provide an introduction to the methodology used to construct the algorithms used by the model.

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. 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.

To simulate the market penetration of processes that use coal to produce liquid fuels, 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. A list of the 26 types of energy, by-products, and factors of production in the coal model is displayed in Table 1.

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

We had planned to have six types of coal. However, we were unable to disaggregate bituminous and subbituminous coal into high and low sulfur fractions and to trace the consumption of the six types of coal.

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.

Materials are 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 crude oil and natural gas production and 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.

The next section of this report will discuss the core model. The subsequent sections will discuss the satellite models. Section 3 will present the oil, gas, and coal supply models. Section 4 will develop the

liquid fuels model. Section 5 will explain the end-use model. Section 6 will present the conclusions.

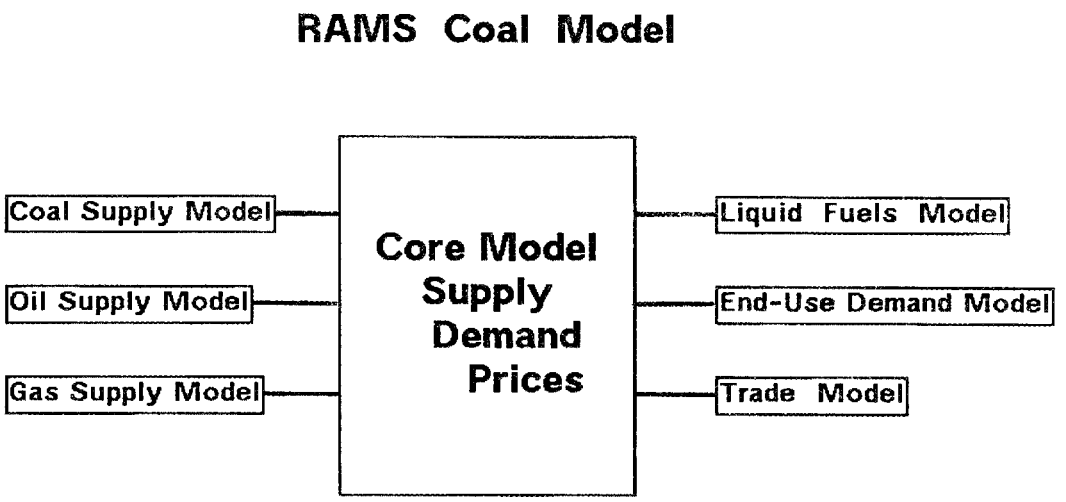

Fig. 1. The Structure of the RAMS Coal Model.

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

2. CORE MODEL

The coal model is an annual model that forecasts energy supply and demand for the United States for the period 1985 to 2030. At the start of each year, all of the coefficients and input variables for the core model are determined. The core model determines the prices and quantities for all of the types of energy and by-products. Given the prices and quantities, the satellite models calculate a new set of coefficients for the next year.

The outputs of the core model are the prices (p[i]) for the 24 produced goods, the output (x[j]) for 11 energy sectors, the inputs to the materials sector (z[i]), and the GNP. The inputs to the core model are the I-O coefficients (a[i,j]) for the 24 goods ([i]) to the 11 sectors ([j]), the potential output of the economy (Output), the coefficients for the materials sector (ca[i]), and the trade(Trade[i]).

Two sets of units are used in the coal model: physical units and value units. The base year values for quantity, price, and value for the 26 factors of production in the coal model are displayed in Table 1. The physical units for the factors of production are given in the table. The price units are billion 1985 dollars per physical unit and the value units are billion 1985 dollars. For example, in 1985 the United States consumed 4.40 billion barrels of crude oil. At an average price of 26.76 dollars per barrel, the value of the oil was 117.83 billion dollars.

For the core model, a convenient set of units for all of the factors of production are the value units. If the quantity of production is measured in billions of 1985 dollars, the base price (BasePrice[i]) can be used to convert to physical units. For example, if the consumption of crude oil in 2000 is 100 billion 1985 dollars worth, then the consumption

is 3.74 billion barrels. For the value units, the prices are price indexes that are equal to 1.0 in 1985. If the price index for crude oil is 1.50, then the price in physical units is 40.14 1985 dollars per barrel.

The first calculation in the core model is to calculate the prices for the 10 energy supply sectors. The price is determined by requiring that the income equal the cost of production:

$$p[j] = \frac{-\sum_{i} p[i]*a[i,j]}{a[j,j]} \qquad \text{for } j = 1 \text{ to } 10 \quad , \tag{1}$$

where the summation over i does not include the jth term.

The energy supply sectors are arranged by distance from primary production. The first 5 sectors have only one input--materials:

$$p[j] = -\ p[24]*a[24,j]/a[j,j] \qquad \text{for } j = 1 \text{ to } 5 \quad . \tag{2}$$

Dry natural gas is before transported gas, which is before distributed gas. Coal and gas are before electricity. To determine prices, the sequence is j = 1 to 10. To determine quantities, the sequence is j = 10 down to 1. If a price is required that has not been determined (for example, p[11], p[14], p[15], and p[24]), the price from the last period is used. The initial values for all of the prices are p[i] = 1.0.

The second calculation in the core model is the demand by the materials sector (z[i]) for the 10 types of energy. The level of output of the materials sector (Output) is exogenous. Thus, z[i] is the product of the I-O coefficient (z[i]/Output) and the Output. The I-O coefficient

depends on the price of energy and is derived from a cost function using Shephard's lemma (for an introduction to cost functions and Shephard's lemma, see Ref. 1). The two-level cost function (G) is given by:

$$G = \sum_i ca[i]*g[i] \quad , \tag{3}$$

where the g[i] are given by:

$$g[i]^{\eta_i} = cb[i]*p[i]^{\eta_i} + (1-cb[i])*p[24]^{\eta_i} \quad . \tag{4}$$

In the first level, Eq. (3), the factors of production are required in fixed proportions. No tradeoffs are allowed. In the second level, Eq. (4), tradeoffs between each of the 23 types of energy and materials are allowed. Thus, the second level simulates energy conservation. To speed the numerical calculation, we assume that $\eta_i = -1.0$.

For the energy sectors (i = 1 to 23), each input-output coefficient is the partial derivative of the cost function with respect to p[i]:

$$z[i]/Output = \frac{\partial G}{\partial p[i]} = ca[i]*cb[i]*(g[i]/p[i])^2 \quad . \tag{5}$$

Thus, the base year cost shares are the product of ca[i] and cb[i]. In the data set CoalBase.Dat, the parameters labeled CA are the base year cost shares.

In most applications of Eq. (4), the parameter η_i is used to control the price elasticity. In the base year, the own price elasticity of demand for z[i] (ϵ_{ii}) is given by:

$$\epsilon_{ii} = -2*(1 - cb[i]) \ . \tag{6}$$

Thus, the parameter cb[i] can be used to control the price elasticity. As cb[i] approaches 1, the elasticity approaches zero. As cb[i] approaches zero, the elasticity approaches -2. We began with all of the cb[i] set equal to 0.5. To obtain a better match with the base case from the National Energy Policy Plan (NEPP),[2] we increased the cb[i] for oil products and reduced the cb[i] for natural gas (see the data set CoalBase.Dat).

Given the Output and the prices for the first 10 types of energy, Eq. (5) determines the energy consumption by the materials sector (z[i]). We use the following expression to estimate the output of the liquid fuels sector x[11]:

$$x[11] = \alpha*f*Output \ . \tag{7}$$

In the base year, f = 1.0 and α is the ratio of x[11] and Output; α = 0.0213. At the end of this section, we will present an equation to determine f in subsequent periods.

Let xa[i] be the consumption of energy of type i by the sectors that do not produce energy of type i:

$$xa[i] = -\sum_{j} a[i,j]*x[j] \quad \text{where } j = 1 \text{ to } 11 \text{ except for } i. \tag{8}$$

For i = 10 down to 1, we determine the output of each energy sector by the following balance equation:

$$x[i]*a[i,i] = z[i] + xa[i] - Trade[i] \quad . \tag{9}$$

The oil and gas supply models determine the domestic oil supply (OilProd) and the domestic gas supply (GasProd). For the crude oil sector, x[5]*a[5,5] = OilProd and Eq. (9) can be used to determine both x[5] and Trade[5]. Similarly, for the natural gas sector, GasProd determines both x[6] and Trade[6]. For the other 8 sectors, Trade[i] is exogenous.

The next calculation in the core model is to determine the supply of goods 11 to 23. Using Eqs. (4) and (5), we calculate the price at which supply is equal to demand. Let z[i] be the demand by the materials sector for good i, where i = 11 to 23. If supply is equal to demand, then:

$$z[i] = Trade[i] + \sum_{j=1}^{11} a[i,j]*x[j] \quad \text{for } i = 11 \text{ to } 23 \quad . \tag{10}$$

Having determined z[i], we can use Eq. (5) to determine the ratio of p[i] and g[i]. Let xb[i] be defined by:

$$xb[i]^{-2} = z[i]/(ca[i]*cb[i]*Output) \quad . \tag{11}$$

Using xb[i], Eq. (5) may be written:

$$p[i] = xb[i]*g[i] \quad . \tag{12}$$

If we solve Eq. (4) for p[i], we find

$$p[i] = (xb[i] - cb[i])*p[24]/(1 - cb[i]) \quad . \tag{13}$$

If cb[i] is larger than xb[i], Eq. (13) will yield a negative value for the price. If a price is negative, a warning message is printed on the output file and the negative price is set equal to 1.0. If a price is negative, the value of cb[i] should be reduced. Large values for cb[i] result in low values for the price elasticity (see Eq. (6)). Thus, an increase in the price elasticity of demand will prevent negative prices.

The next calculation in the core model is to determine the prices and quantities of goods 24 to 26: capital, labor, and materials. We will also calculate the GNP and Value Added. For capital and labor, the prices are always equal to 1.0 and cb[i] = 1.0. Thus, g[i] = p[i] = 1.0 and Eq. (5) determines the inputs of capital and labor to the materials sector:

$$z[i] = ca[i]*\text{Output} \quad \text{for } i = 25 \text{ and } 26 \quad . \tag{14}$$

The Value Added is the sum of the payments to labor and capital. Since the prices are equal to 1.0, the Value Added = z[25] + z[26].

The price of materials (p[24]) is equal to G and is determined by Eq. (3). Thus, p[24] depends on the g[i]. Equation 1 determines the first 10 prices and Eq. (4) can be used to calculate the first 10 values for

g[i]. Equations (12) and (13) can be used to determine p[i] and g[i] for i = 11 to 23. For the input of materials to the materials sector, cb[24] = 1.0 and g[24] = p[24]. Since g[i] = 1.0 for i = 25 and 26, all of the g[i] except g[24] are known and we can solve Eq. (3) for p[24]:

$$p[24] = xc/(1 - ca[24]) \quad , \tag{15}$$

where xc is defined by:

$$xc = \sum_{i=1}^{26} ca[i]*g[i] \quad , \tag{16}$$

where the summation does not include the i = 24 term.

The quantity of materials is exogenous and is called Output. Materials are consumed to conserve energy, to produce materials, to produce energy, to produce imported energy, and to provide goods and services to consumers (the GNP). To calculate the GNP, we subtract from Output all of the materials that are used for other purposes.

The I-O coefficient for each type of energy was derived by taking the partial derivative of the cost function with respect to each of the energy prices (see Eq. (5)). The I-O coefficient for materials has a contribution from each of the energy sectors and from materials:

$$z[24]/Output = \sum_{i=1}^{24} ca[i]*(1 - cb[i])*(g[i]/p[24])^2 \quad . \tag{17}$$

z[24] includes the materials consumed to conserve energy and to produce materials.

Let xd be the materials consumed to produce energy:

$$xd = -\sum_{j=1}^{11} a[24,j]*x[j] \quad . \tag{18}$$

Then the GNP is given by:

$$GNP = Output - z[24] - xd + Trade[24] \quad . \tag{19}$$

If the core model were solved repeatedly to obtain equilibrium values for the prices and quantities, the value of the GNP would be equal to the value added:

$$p[24]*GNP = Value\ Added \quad . \tag{20}$$

However, the core model is only solved once each year.

In general, the income will not be equal to the expenses for the liquid fuels sector. The factor (f) in Eq. (7) is designed to balance income and expenses. If the income is higher than expenses, output is increased and vice versa. Define unit income and expenses for the liquid fuels sector by:

$$Income = \sum_{i} p[i]*a[i,11] \quad , \text{ whenever } \quad a[i,11] > 0 \tag{21}$$

and

$$\text{Expenses} = -\sum_{i} p[i]*a[i,11] \quad , \text{ whenever } \quad a[i,11] < 0 \tag{22}$$

Let rp be the ratio of expenses and income:

$$rp = \text{Expenses}/\text{Income} \quad . \tag{23}$$

If rp is greater than 1.0, we want reduce output. The equation for the factor (f) is:

$$f(t+1) = f(t)/rp \quad . \tag{24}$$

We have completed our discussion of the core model. The core model calculates prices and quantities for the produced goods and services, given I-O coefficients for the sectors. Subsequent sections of this report will describe how the values of the I-O coefficients are changed by other sections of the model.

3. THE SUPPLY MODELS

This section will describe the supply models for oil, gas, and coal. Each of the supply models is similar to the supply model in the RAMSGAS model.[3] There are several sources of supply for each of the fuels: 4 sources of oil, 14 sources of gas, and 13 sources for the 4 types of coal. Each of sources of fuel has a production cost that depends on cumulative consumption of the resource. Given the production cost, a market share is calculated. Given the market share, an average price is calculated and the I-O coefficients are calculated. The core model determines the level of consumption. Given the level of consumption and the market share, the cumulative consumption of each of the sources of supply is calculated and the model is ready for the next period.

Each of the N sources of fuel has a production cost (PW[i]) that depends on cumulative consumption of the resource (Q[i]):

$$PW[i] = PS[i]*(QF[i] - QS[i])/(QF[i] - Q[i]) \quad , \qquad (25)$$

where PS is the initial production cost, QS is the initial consumption of the resource, and QF is the ultimate consumption of the resource. Initially, Q = QS and PW = PS. As Q approaches QF, the production cost increases without a limit. Equation (24) is a special case of a function that was introduced in Ref. 4.

For oil and gas, the production cost influences the level of drilling, while for coal the production cost influences the level of production. For oil and gas, drilling of a successful oil or gas well results in production for a long time (15 to 25 years). A sudden increase or decrease in world

oil price can have a large impact on drilling but will have a smaller impact on production.

Market shares (SA[i]) for each of the N sources of fuel are determined by a logit function and are inversely proportional to the production cost:

$$SA[i] = SB[i]*PW[i]^{\gamma}/(\sum_{j} SB[j]*PW[j]^{\gamma}) \quad , \tag{26}$$

where SB[i] is the base market share and γ is a negative parameter.

For oil and gas, the initial year of production (STYR[i]) and the world oil price (WOP) have an influence on the market shares. For new technologies, a lengthy period of research and development is required before the commercial introduction of the technology. The parameter STYR is used to simulate the R&D process; the market share is zero before the initial year of production. If the production cost for oil is greater than the WOP, then the market share is zero and no wells will be drilled. If the production cost of gas is greater than the BTU equivalent of the WOP (WOP/5.8 Million BTU per Barrel), then the market share is zero.

For the coal model, each of the 4 types of coal can be shipped to either of the two demand regions: east and west. The market share depends on the delivered cost, the sum of the mine-mouth cost and the transportation cost. Each type of coal has a base market share for both of the demand regions. Coal production does not have an initial year of production and does not depend on the WOP. The coal supply model has a lag parameter to control the rate of change of the market shares.

The average cost of production (PA) is the sum of the products of the individual production costs and the market shares:

$$PA = \sum_{i} PW[i]*SA[i] \quad . \tag{27}$$

For the 4 types of coal and for natural gas, the average cost of production is used to calculate the I-O coefficient for the amount of materials required to produce fuel (see Eqs. (1) and (2)). For crude oil, the WOP is used to calculate the I-O coefficient for materials.

Each year, the supply models update the production costs and I-O coefficients for crude oil, natural gas, and coal. Next, the core model calculates the production level for each type of fuel. Finally, the supply models update the cumulative consumption of each type of fuel.

For oil and gas, the supply models must forecast the level of discoveries of oil and gas. Since the two models are similar, we will confine our attention to the oil model. Let PO be the average production cost for oil; PO is calculated using Eq. (27). Let BO be the profit margin, the difference between the world oil price and the cost of oil production, in the base year. Let FO be the ratio of the profit margin in each year to BO:

$$FO = (WOP - PO)/BO \quad . \tag{28}$$

In the base year, FO = 1.0. If FO is negative, we set it equal to 0.0. If FO is greater than the parameter UpperOil, then we set FO equal to UpperOil. The quantity of oil that will be discovered each year (QuanOil) is given by:

$$QuanOil = FO*BaseOil \quad , \tag{29}$$

where BaseOil is the oil production in the basc year measured in physical units.

The quantity of oil that is discovered each year depends on the profit margin. When the profits are higher than the base year profits, the level of discoveries can increase until the upper bound (provided by UpperOil) is reached. When the WOP drops and profits decrease, the level of discoveries decreases. Over time, the cost of production will increase and an increase in WOP will be required to prevent a decrease in discoveries.

The amount of oil that is discovered in each of the oil producing regions is the product of QuanOil and the market share (SA[i]). The cumulative discoveries of oil (Q[i]) are given by:

$$Q[i] = Q[i] + QuanOil*SA[i] \quad . \tag{30}$$

If Q[i] is greater than the total resource (QF[i]), then we reduce Q to Q[i] = 0.999*QF[i].

The amount of oil or gas that was discovered will be produced over a long time; 19 years for oil and 23 years for gas. For oil and gas, we define a production profile (Prof[k]). If OilProd[t] is the oil production in year t, then the future oil production in value units is given by:

$$OilProd[t+k] = OilProd[t+k] + QuanOil*BasePrice[5]*Prof[k] \quad . \tag{31}$$

For coal supply, the core model provides the total production of each of the four types of coal. The coal supply model allocates the production to the two demand regions and uses the market shares to calculate the

production for each of the 13 sources of coal. The cumulative production is calculated using an equation like Eq. (30).

4. THE LIQUID FUELS MODEL

The liquid fuels model simulates the market penetration of conventional and unconventional processes for producing liquid fuels and by-products from coal, shale, tar sands, and heavy oil. For each year from 1985 to 2030, the model calculates the market share for each of the 19 processes in the model. Given the market shares for the processes, the model calculates new I-O coefficients for the liquid fuels sector (sector 11). The model also calculates the total installed capacity for each process.

Each of the 19 processes is described by a process summary sheet (see Appendix B of the User's Guide). Using the process summary, I-O coefficients (AP[i,n]) are calculated for the processes. Using a discounted cash flow (DCF) method that will be described later in this section, the discounted value of the revenue requirements and the discounted value of the income are calculated for each process in each year. Let PP[n] be the ratio of the revenue requirements and income. PP[n] is a figure of merit for a process. When PP[n] is greater than 1.0, the process would lose money.

Using PP[n] as the cost of each process, we calculate market shares (SA[n]) using Eq. (26). The market shares are the share of new investment that is captured by each process. Each process has an introduction year, the market shares are zero before the introduction year. Furthermore, if PP[n] is greater than 2.0 for a process, the market share is zero.

We use a lag parameter (μ) to control the penetration rate for the new technologies:

$$a[i,11] = (1 - \mu)*a[i,11] + \mu*\sum_{n} SA[n]*AP[i,n] \quad . \tag{32}$$

Let ZP[n] be the total installed capacity of each process, then:

$$ZP[n] = (1 - \mu)*ZP[n] + \mu*SA[n]*x[11] \quad . \tag{33}$$

We have calculated a new set of I-O coefficients and the model is ready for the next period.

The remainder of this section will present the DCF model. Two versions of the DCF model were developed: DCFShort and DCFLong. For the long version, a table of income and expenses was developed for each year of the project and the discounted present values were calculated from the table. The short version gives the same results as the long version; however, analytical formulas are used to speed the calculation. For a test case, the short version was 30 times as fast as the long version. The long version was based on the computer code PRP,[5,6] while the short version was based on the formulas in Ref. 7.

The basic input parameters for the DCF model are displayed in Table 2 of the User's Guide. Two types of financing are allowed: debt and equity. The interest rate is the weighted average of the two rates. The after tax rate is the interest rate minus the tax on the debt payment. The discount rate is a controversial parameter. Initially, we used 1.0 plus the after tax rate. However, when we varied the inflation rate for all of the inputs and outputs from 0% to 5% to 10%, the results were not invariant. To make the results invariant, we assume that the discount rate (d) is exp(interest rate).

The first function that is calculated by the DCF model is EscFun[i,T]. To define EscFun[i,T], we will derive the discounted present value of the

income for a project. Let y[i] be the amount of good i produced by the project each year (we assume that y[i] does not depend on time t). Let p[i,t] be the price of good i in year t. We assume that the price escalates at a uniform rate from a base price:

$$p[i,0] = \text{BasePrice}[i] \text{ and } p[i,t+1] = e[i]*p[i,t] \quad ,$$

where e[i] is the escalation rate for good i.

If d is the discount rate, the discounted present value of the income (v) is:

$$v = \sum_{t=1}^{T} \sum_{i} p[i,t]*y[i]/d^{t} \quad . \tag{34}$$

If we define EscFun[i,T] by:

$$\text{EscFun}[i,T] = \sum_{t=1}^{T} (e[i]/d)^{t} \quad , \tag{35}$$

then Eq. (34) can be written:

$$v = \sum_{i} \text{EscFun}[i,T]*\text{BasePrice}[i]*y[i] \quad . \tag{36}$$

Introduction of the function EscFun[i,T] reduces computation time by reducing the double summation in Eq. (34) to a single summation in Eq. (36).

To compute EscFun[i,T], we use the following formula:

$$\text{EscFun}[i,T+1] = (e[i]/d)*(1 + \text{EscFun}[i,T]) \quad . \tag{37}$$

To help us calculate the present value of the book depreciation and the salvage value, we define EscFunA[T] and Dinv[T] by:

$$\text{EscFunA}[T] = \sum_{t=1}^{T} t*(e[26]/d)^{t} \quad , \text{ and} \tag{38}$$

$$\text{Dinv}[T] = (e[26]/d)^{T} \quad , \tag{39}$$

where e[26] is the escallation rate for capital.

The capital cost for each process is the instantaneous capital cost; the cost of construction at one date. The actual construction will require several years--the leadtime. The total capital cost will include the instantaneous capital cost, inflation, and interest during construction. The function InvFun[T] is the ratio of the total capital cost and the instantaneous capital cost. A formula for the function InvFun[T] will be derived in the following paragraphs.

We assume that the rate of construction is uniform. Thus, the annual investment without inflation is BaseCost/LT, where LT is the leadtime. We assume that the inflation rate is CapEsc. Let Invest[k] be the investment in each year:

$$\text{Invest}[k] = \text{BaseCost}*\text{CapEsc}^{k-1}/\text{LT} \quad \text{for } k = 1\text{-LT to } 0 \quad . \tag{40}$$

We assume that investment is made at the start of a year and that interest is paid at the end of each year. The total capital investment at the start of a year is equal to the investment at the end of the previous year plus the new investment:

$$\text{CpStrt}[k] = \text{CapEnd}[k-1] + \text{Invest}[k] \quad . \tag{41}$$

The investment at the end of a year is equal to the investment at the start of the year plus the interest:

$$\text{CapEnd}[k] = (1 + \text{InterestRate})*\text{CapStrt}[k] \quad . \tag{42}$$

Finally, the InvFun[LT] is the ratio of the total investment and the BaseCost:

$$\text{InvFun}[LT] = \text{CapEnd}[0]/\text{BaseCost} \quad . \tag{43}$$

The revenue requirements for a project (RR) are an income stream that will pay all of the operating costs and capital costs for the project. The costs that the revenue requirements will pay include: the operating and maintenance costs (O), the property tax and insurance (PT), the book depreciation (DB), amortization of the investment (r*V), and income tax (TX). The revenue requirements are reduced by the tax credit (TC) and the salvage value of the capital stock (S). The balance equation for the revenue requirements may be written:

$$RR = O + PT + DB + r*V + TX - TC - S \quad . \tag{44}$$

The interest rate (r) is a weighted average of the interest rates for debt (r_b) and equity (r_s):

$$r = r_b*f_b + r_s*f_s \quad , \tag{45}$$

where the sum of the debt fraction (f_b) and the equity fraction (f_s) is 1.0. Since interest is deductible on income tax, the after tax interest rate (u) is given by:

$$u = (1-\tau)*r_b*f_b + r_s*f_s \quad , \tag{46}$$

where τ is the income tax rate:

$$\tau = \text{StateTax} + (1 - \text{StateTax})*\text{FedTax} \quad . \tag{47}$$

The income tax payment (TX) is equal to the product of the income tax rate and the taxable income. The taxable income is equal to the revenue requirements plus the salvage value and minus the operating costs, the property tax, the tax depreciation, and the interest:

$$TX = \tau*\{RR + S - O - PT - DT - r_b*f_b*V\} \quad . \tag{48}$$

Using Eq. (48) to eliminate the income tax payment from Eq. (44), we derive the following equation for the revenue requirements:

$$RR = O + PT - S + [1/(1-\tau)]*\{DB + u*V - TC - \tau*DT\} \quad . \tag{49}$$

The DCF model calculates the discounted present value of each term in Eq. (49). If K is the total plant investment, we can derive the following expressions for the annual values of DB, V, and DT:

$$DB = K/BL \quad , \tag{50}$$

$$V = K*\{1 - [(t-1)/BL]\} \quad , \text{ and} \tag{51}$$

$$DT = (K - S)/TL \quad , \tag{52}$$

where BL is the book life and TL is the tax life.

The total plant investment (K) is equal to the base cost multiplied by InvFun[LT] plus the startup cost. The present value of the tax depreciation is given by Eq. (52) and EscFun:

$$DT = DT*EscFun[26,TL] \quad , \tag{53}$$

(we will use the same symbol for both the annual value of the terms in Eq. (49) and for their discounted present values).

The present value of the book depreciation and amortization is given by Eqs. (50) and (51) and by EscFun and EscFunA:

$$DB = DB*EscFun[26,BL] \quad , \tag{54}$$

$$V = (BL + 1)*DB*EscFun[26,BL] - DB*EscFunA[BL] \quad , \tag{55}$$

Using the I-O coefficients for the process (AP), the current prices (p), and EscFun, the present values of the income and operating expenses are determined:

$$\text{Income} = \sum_i p[i]*AP[i,n]*EscFun[i,L] \quad , \text{ if } \quad AP[i,n] > 0 \quad , \tag{56}$$

and

$$\text{Expenses} = -\sum_i p[i]*AP[i,n]*EscFun[i,L] \quad , \text{ if } \quad AP[i,n] < 0 \quad , \tag{57}$$

where L is the lifetime of the project. The expressions for income and expenses apply if the load factor is 100%. If the load factor (FL) is less than 100%, the income and expenses will be reduced:

$$O = FL*\text{Expenses} \quad . \tag{58}$$

Let FP be the sum of the property tax rate and the insurance rate. The present value of property tax and insurance are given by:

$$PT = FP*K*EscFun[26,L] \quad . \tag{59}$$

Let FT be the tax credit rate. The present value of the income tax credit is given by:

$$TC = FT*K/d \quad . \tag{60}$$

The present value of the salvage value of the plant is given by:

$$S = S*Dinv[L] \quad . \tag{61}$$

Since we have calculated the present value of all of the terms in Eq. (49), we can calculate the present value of the revenue requirements. The present value of the income is the product of the full capacity income (Eq. (56)) and the load factor (FL). The output of the DCF model is the ratio of the revenue requirements and income for each process (PP[n]).

5. THE END-USE MODEL

Energy is an intermediate good that is consumed by capital equipment to provide energy services. Examples of energy services are space heat, process heat, lighting, mechanical drive, and passenger transport. Often several options are available to provide each energy service. For example, space heat can be provided by furnaces that burn oil, gas, LPG, coal, or wood; or by electric resistance heaters; or by electric heat pumps. Intercity passenger transport can be provided by automobile, bus, train, or airplane.

All sectors of the economy use energy services. To create an end-use energy demand model, we subdivide the economy into markets. For example, residential space heat or industrial process heat. For each market, we can identify one or more options that use different fuels to provide the same energy service. The end-use model allows coal to replace expensive oil and gas in the various markets.

In the coal model, the materials sector is the energy demand side of the economy. The end-use model forecasts how the I-O coefficients for the materials sector (ca[i]) respond to changes in prices of fuels and factors. We have subdivided the materials sector into 42 markets. For each market, the model has one or more options. Each option is described by I-O coefficients: AE[m,o,i] where m is the market, o is the option, and i is type of good or service. The cost of energy service from each option (OC[m,o]) is determined by the I-O coefficients and the prices:

$$OC[m,o] = \sum_{i} p[i]*AE[m,o,i] \quad . \tag{62}$$

Each year, the materials sector installs a new vintage of capital stock. The market share for each option in the new vintage (OS[m,o]) depends on the option cost and is determined by a logit function:

$$OS[m,o] = OC[m,o]^{\gamma} \; / \sum_{o} OC[m,o]^{\gamma} \quad , \tag{63}$$

where γ is a negative parameter that can be specified for each market ($\gamma = \gamma[m]$).

In the base year, the average cost of energy service for each market (BC[m]) is determined by the option costs and the market shares:

$$BC[m] = \sum_{o} OC[m,o]*OS[m,o] \quad . \tag{64}$$

Let D[m] be the fraction of the total inputs to the materials sector in the base year that is required to provide energy services to market m. The D[m] are positive and satisfy:

$$\sum_{m} D[m] = 1.0 \quad . \tag{65}$$

The I-O coefficients for the new vintage of capital stock (AM[i]) are determined by adding up the market shares for each option in each market:

$$AM[i] = \sum_{m} \sum_{o} AE[m,o,i]*OS[m,o]*D[m]/BC[m] \quad . \tag{66}$$

In the base year, the new vintage I-O coefficients satisfy:

$$\sum_i p[i]*AM[i] = 1.0 \quad . \tag{67}$$

The average I-O coefficients for the materials sector respond gradually to the changes in the energy consumption patterns of the new vintage:

$$ca[i] = (1 - \mu)*ca[i] + \mu*AM[i]/cb[i] \quad , \tag{68}$$

where μ is a lag parameter.

6. CONCLUSIONS

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. A list of the 26 types of energy, by-products, and factors of production in the coal model is displayed in Table 1.

The coal model I-O structure has 13 sectors to produce the first 24 goods in Table 1 (the last 2 factors, labor and capital, are exogenous inputs). The first 10 sectors produce the first 10 goods. Sector 11, the liquid fuels sector, produces the goods from 11 to 23. Sector 12 produces good 24, materials. The final sector, sector 13, is the trade sector.

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. Given 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.

This report has presented the equations for the core model and for all of the existing satellite models. The supply models (oil, gas, and coal) calculate the I-O coefficients for the first 6 sectors. The liquid fuels model calculates the coefficients for sector 11. The end-use model

calculates the coefficients for sector 12. The remaining sectors (7 to 10) have fixed coefficients.

7. REFERENCES

1. H. R. Varian (1984). **Microeconomic Analysis**, W. W. Norton & Company, New York, New York.

2. A. Haynes, et. al. (1985). **"National Energy Policy Plan Projections to 2010,"** DOE/PE-0029/3, U.S. Department of Energy, Washington, DC.

3. E. A. Browne, et. al. (1986). **"The Research and Development Analysis Modeling System World Natural Gas Model (RAMSGAS): Final Documentation,"** ORNL/TM-10157, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

4. D. B. Reister and R. M. Rotty (1983). **"Simple Models for the Consumption Rate of Fossil Fuel,"** **Energy**, Vol. 8(4), 283-289.

5. R. Salmon (1977). **"PRP - A Discounted Cash Flow Program for Calculating the Production Cost (Product Price) of the Product from a Process Plant,"** ORNL-5251, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

6. R. Salmon (1983). **"PRP-4: An Updated Version of the Discounted Cash Flow Program PRP,"** ORNL-5723, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

7. D. L. Phung (1984). **"Cost Comparison of Energy Projects: Discounted Cash Flow and Revenue Requirement Methods,"** ORAU/IEA-80-8(M), Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

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