3/11
3/21/79

Lh. 2360

ORNL/TM-5953

Fossil
Energy
Program

MASTER

Survey and Evaluation of Current and Potential Coal Beneficiation Processes

Suman P. N. Singh
G. R. Peterson

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

DISCLAIMER

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $11.75; Microfiche $3.00

ORNL/TM-5953
Dist. Category UC-90d

Contract No. W-7405-eng-26
CHEMICAL TECHNOLOGY DIVISION

Coal Technology Program

SURVEY AND EVALUATION OF CURRENT AND POTENTIAL COAL BENEFICIATION PROCESSES

Suman P. N. Singh
G. R. Peterson*

Prepared for the

Department of Energy/Fossil Energy
Program Control and Support Division
Engineering Economic and Standards Section

Date Published: March 1979

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

---

*Retired.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

CONTENTS

Page

Page

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

EXECUTIVE SUMMARY

Coal beneficiation is a generic term that is used to designate various operations performed on run-of-mine (ROM) coal to prepare it for specific end uses, such as feed to a coke oven or a coal-fired boiler or use in a coal conversion process. It is also referred to as coal preparation or coal cleaning. Over the years, coal beneficiation has come to encompass the entire spectrum of operations ranging from the relatively simple crushing and size classification operations to rather elaborate chemical and microbiological processes that are used (or are being developed) to render the ROM coal more suitable for the end use.

Coal beneficiation offers a significant, though often overlooked, means of reducing the sulfur and mineral matter content of several coals thereby offering a plausible and, in many cases, economic solution to the problem of burning high-sulfur coals in an environmentally acceptable manner. Moreover, beneficiating the coal also results in:

- lower transportation costs per unit of energy delivered;
- lower waste disposal costs at the user facility;
- improved coal handling capabilities;
- higher combustion efficiency in the furnace; and
- reduced slagging in the furnace, which translates into reduced downtime for the furnace.

A survey of currently used and potential coal beneficiation technologies was undertaken to assimilate and evaluate the information regarding the known coal beneficiation technologies. The results of the survey are presented in this report.

The publicly known coal beneficiation technologies are summarized in Table 1.1 (see p. 4). Three of the processes included in this table were subjected to a more-detailed evaluation: (1) the wet mechanical beneficiation process, (2) the Battelle hydrothermal coal process, and (3) the TRW-Meyers fine coal process. These processes were selected for a more-detailed evaluation because:

1. The processes are either commercial or are farthest along the development ladder to commercialization.
2. Process design information is available.
3. They offer a means of comparing commercially used and potential coal beneficiation technologies.

To evaluate the beneficiation processes in a cogent manner, representative coals from significant coal beds across the country were identified and selected to form a basis for the study. A list of these representative coals and their analyses is presented in Table 1.2 (see p. 5). In the interest of time, a subset of three coals selected from the above list was used for the more detailed evaluation of the above-mentioned three beneficiation processes. These three coals were selected because:

1. They have high sulfur and ash levels.
2. They are prime candidates for the application of beneficiation processes.
3. They represent significant coal beds in the country.

The three coals selected were: (1) a bituminous coal from the lower Kittanning coal seam located in Somerset County, Pennsylvania; (2) a bituminous coal from coal bed No. 6 located in Hopkins County, western Kentucky; and (3) a bituminous coal from coal bed No. 6 located in Williamson County, Illinois. These coals will hereinafter be referred to simply as Pennsylvania, western Kentucky, and Illinois coals respectively. The remaining coals listed in Table 1.2 have sulfur contents that are either within the current permissible SO_x emission level (that is, 1.2 lb SO_2 per million Btu) or are slightly higher than the permissible level. The noncompliance coals can be cleaned to yield compliance coal (that is, coal which meets the current permissible SO_x emission level) by using wet mechanical beneficiation processes. A brief description of the possible treatment of these coals is presented in Sect. 1.4.

Information on the processes listed in Table 1.1 was gathered from various openly available sources. No proprietary information was obtained or used in the evaluation. Several of the coal beneficiation processes evaluated in this report are under development and have not yet been commercialized. These experimental processes were evaluated on the basis of available information. However, more detailed evaluations (consisting of process designs and economic analyses) were performed for the three above-mentioned processes based on conceptual plants with production levels of 1500 and 15,000 tons/day of moisture- and ash-free (maf) cleaned product coal. These production levels correspond approximately to 2300 and 23,000 tons/day of ROM feed coal. A summary of the information developed regarding these three processes is presented in Table ES.1 for the grassroots-type facilities and in Table ES.2 for the battery-limits type facilities. By definition, a grassroots facility is one for which all of the utilities required by the plant are generated onsite; for the battery-limits facility, the required utilities are available (from an existing plant, for example) and can be purchased.

The following conclusions about the three selected coal beneficiation processes can be derived from the information given in Tables ES.1 and ES.2:

1. The processes are capable of reducing the total sulfur content of the coals from 25 to 80% and the ash content from 30 to 75%. Generally, higher sulfur reductions are obtained when the coals are chemically cleaned; however, mechanical beneficiation processes appear to remove a greater amount of the ash content of the coal. Also, it should be noted that the ash content of the cleaned product coal from the Battelle hydrothermal coal process (BHCP) apparently increases. This is because the leachant (NaOH) impregnates the coal.

2. The material and thermal recoveries from most of the conceptual plants evaluated are generally high, ranging between ~70 and 95%. By definition, material recovery is the ratio of the mass of the cleaned product coal divided by the mass of the feed coal to the plant, whereas thermal recovery is the ratio of the heating value of the maf product coal divided by the heating value of the maf feed coal. It should be noted, however, that the material and thermal recoveries are relatively low (~45 to 60% for the grassroots-type BHCP plant. This is because a significant amount

Table ES.1. Summary of information regarding coal beneficiation processes evaluated - for grassroots facilities

	1500-ton/day[a] maf product coal facilities						15,000-ton/day[b] maf product coal facilities					
	Percent reduction		Percent recovery		Beneficiation cost[c]		Percent reduction		Percent recovery		Beneficiation cost[c]	
Process description	Sulfur	Ash	Material[d]	Thermal[e]	$/ton[f]	$/MMBtu[g]	Sulfur	Ash	Material[d]	Thermal[e]	$/ton[f]	$/MMBtu[g]
Wet beneficiation process												
Mild cleaning												
Pennsylvania coal[h]	26.6	46.6	73.9	86.8	6.03	0.24	26.6	46.6	74.6	87.6	3.93	0.16
W. Kentucky coal[h]	25.5	57.1	80.3	88.6	6.26	0.25	25.5	57.1	81.3	89.6	3.92	0.15
Illinois coal[h]	25.7	37.3	85.4	92.5	5.84	0.25	25.7	37.3	87.5	93.9	3.65	0.16
Deep cleaning												
Pennsylvania coal	43.4	72.8	69.1	88.0	8.06	0.30	43.4	72.8	70.4	89.7	5.43	0.20
W. Kentucky coal	27.8	74.4	76.3	86.5	8.36	0.30	27.8	74.4	77.8	88.1	4.99	0.19
Illinois coal	33.5	57.9	77.4	87.4	7.64	0.31	33.5	57.9	79.1	89.3	5.09	0.21
Battelle hydrothermal process												
Pennsylvania coal	79.3	i	49.5	45.1	59.51	3.12	79.3	i	49.5	45.0	47.19	2.47
W. Kentucky coal	75.7	i	60.4	53.6	50.60	2.46	75.7	i	60.4	53.6	40.09	1.95
Illinois coal	69.6	i	56.1	50.3	50.43	2.76	69.6	i	56.1	50.4	42.18	2.18
TRW-Meyers fine coal process												
Pennsylvania coal	78.6	30.0	82.0	88.2	12.43	0.54	78.6	30.0	82.1	88.2	7.30	0.32
W. Kentucky coal	60.8	30.0	86.0	89.5	13.97	0.57	60.8	30.0	86.0	89.6	8.21	0.34
Illinois coal	56.8	30.0	84.0	88.0	13.52	0.59	56.8	30.0	84.0	88.0	7.88	0.34

[a] Hours of operation: wet beneficiation processes = 8 hr/day; Battelle hydrothermal and TRW-Meyers processes = 24 hr/day.

[b] Hours of operation: wet beneficiation processes = 16 hr/day. Battelle hydrothermal and TRW-Meyers processes = 24 hr/day.

[c] Basis: ROM coal cost = $20/ton; debt/equity = 70:30; annual after-tax rate of return on equity = 12%; annual interest rate on debt = 9%.

[d] Based on moisture-free coal.

[e] Based on maf coal.

[f] For moist, cleaned product coal (nominal 5% moisture).

[g] Based on heating value of maf cleaned product coal.

[h] See page viii for specific coal type.

[i] Apparent ash content increased because leachant (NaOH) impregnates the product coal.

Table ES.2. Summary of information regarding coal beneficiation processes evaluated - for battery-limits facilities

Process description	1500-ton/day[a] maf product coal facilities						15,000-ton/day[b] maf product coal facilities					
	Percent reduction		Percent recovery		Beneficiation cost[c]		Percent reduction		Percent recovery		Beneficiation cost[c]	
	Sulfur	Ash	Material[d]	Thermal[e]	$/ton[f]	$/MMBtu[g]	Sulfur	Ash	Material[d]	Thermal[e]	$/ton[f]	$/MMBtu[g]
Wet beneficiation process												
Mild cleaning												
Pennsylvania coal[h]	26.6	46.6	74.9	88.0	5.06	0.21	26.6	46.6	75.3	88.5	3.97	0.16
W. Kentucky coal[h]	25.5	57.1	81.7	90.1	5.18	0.20	25.5	57.1	81.9	90.3	3.97	0.16
Illinois coal[h]	25.7	37.3	86.9	94.1	4.81	0.21	25.7	37.3	87.5	94.8	3.66	0.14
Deep cleaning												
Pennsylvania coal	43.4	72.8	70.8	90.1	6.87	0.26	43.4	72.8	71.2	90.7	5.56	0.21
W. Kentucky coal	27.8	74.4	78.6	89.1	6.98	0.27	27.8	74.4	78.9	89.4	5.12	0.20
Illinois coal	33.5	57.9	79.7	90.0	6.31	0.26	33.5	57.9	80.1	90.4	5.22	0.21
Battelle hydrothermal process												
Pennsylvania coal	79.3	i	97.2	92.8	62.09	3.25	79.3	i	97.2	92.8	63.37	3.32
W. Kentucky coal	75.7	i	100.0	93.5	55.74	2.71	75.7	i	100.0	93.5	52.33	2.55
Illinois coal	69.6	i	99.1	88.9	56.55	2.92	69.6	i	99.1	88.9	56.46	2.92
TRW-Meyers fine coal process												
Pennsylvania coal	78.6	30.0	84.4	90.8	12.06	0.53	78.6	30.0	84.4	90.8	7.99	0.35
W. Kentucky coal	60.8	30.0	88.5	92.1	13.29	0.55	60.8	30.0	88.5	92.2	8.64	0.35
Illinois coal	56.8	30.0	86.4	90.5	13.13	0.57	56.8	30.0	86.5	90.6	8.62	0.38

---

[a] Hours of operation: wet beneficiation processes = 8 hr/day; Battelle hydrothermal and TRW-Meyers processes = 24 hr/day.

[b] Hours of operation: wet beneficiation processes = 16 hr/day; Battelle hydrothermal and TRW-Meyers processes = 24 hr/day.

[c] Basis: ROM coal cost = $20/ton; debt/equity = 70:30; annual after-tax rate of return on equity = 12%; annual interest rate on debt = 9%.

[d] Based on moisture-free coal.

[e] Based on maf coal.

[f] For moist, cleaned product coal (nominal 5% moisture).

[g] Based on heating value of maf cleaned product coal.

[h] See page viii for specific coal type.

[i] Apparent ash content increased because leachant (NaOH) impregnates the product coal.

of the cleaned product coal produced is diverted in the plant to provide the process steam and electric power requirements.

3. Beneficiation costs for cleaning the coals by the different processes range between \$4 and \$64 per ton of product coal. When translated into dollars per million Btu, these costs range between \$0.14 and \$3.32 per million Btu. Generally, the beneficiation costs vary with the degree of cleaning achieved and with the complexity of the cleaning process — that is, the greater the sulfur reduction obtained and the more complex the process, the higher the beneficiation cost.

4. The chemical beneficiation processes (BHCP and TRW-Meyers fine coal process), although providing much greater sulfur reduction than the mechanical (wet) beneficiation processes, are also more expensive than the mechanical beneficiation processes. Hence, by implication, the chemical beneficiation processes are not cost competitive with the mechanical processes. However, future process developments and/or environmental constraints on coal processing plants may alter this conclusion.

The present study is intended to provide information on several coal beneficiation processes. For those processes with sufficient available information to perform conceptual designs, process designs were developed for conceptual plants and economic evaluations were performed. For the other beneficiation processes (which are at various levels of process development), process descriptions have been provided in the report commensurate with the amount of information and time available to evaluate the process.

The basic objective of this report is twofold:

1. to draw attention to the fact that coal beneficiation not only offers a viable and often economical means of reducing the sulfur and the mineral matter content of several high-sulfur U.S. coals so that the coals can be burned in an environmentally acceptable manner but also has several other benefits which have been mentioned earlier in the executive summary; and

2. to present information about potential processes that are currently being developed to beneficiate coal.

Because of severe time constraints, several of the potential coal beneficiation processes listed in Table 1.1 could not be evaluated in depth. An in-depth evaluation of these processes should be conducted in addition to the present study to more fully appreciate the potentially important role that beneficiation can play in the clean burning of coal to meet the nation's future energy needs.

PAGES 1 to 2

WERE INTENTIONALLY

LEFT BLANK

altogether. To evaluate the potential benefits of the technology, DOE/Fossil Energy requested ORNL to conduct a study of the coal beneficiation processes.

1.1 Objective

The objective of the study was to identify and analyze the various currently used and potential coal beneficiation technologies.

1.2 Introductory Remarks

To achieve the above-stated objective, the following steps were taken.

1.2.1 Identification of processes

The technical literature was scanned to identify the various coal beneficiation technologies that primarily reduced the sulfur and the mineral matter (ash) contents of coals without destroying the physical character of the coal; that is, coal liquefaction type processes were excluded from consideration. Table 1.1 is a list of coal beneficiation technologies that were identified. These processes were evaluated (to varying degrees) in this study.

With the exception of the Ilok and a few of the chemical coal beneficiation processes, most of the beneficiation technologies listed in Table 1.1 remove only the pyritic sulfur and the mineral matter from the ROM coal. The Ilok and the few chemical coal beneficiation processes mentioned above claim to remove not only the pyritic sulfur but also a fraction of the organically bound sulfur that occurs in coal.

1.2.2 Selection of representative coals

Representative coals from various significant coal beds across the country were identified and selected to form a basis for the study. Table 1.2 is a list of the selected coals together with pertinent data about the coals. The information given in this table was obtained from the U.S. Bureau of Mines Report of Investigations No. 8118[1] and Bulletin No. 567.[2]

Table 1.1. Beneficiation processes evaluated

PHYSICAL AND MECHANICAL BENEFICIATION PROCESSES

- Dry Mechanical Beneficiation
  - Crushing and screening
  - Centrifugal separation
  - The Magnex process
  - Dry high-gradient magnetic separation
  - Dry table separator
  - The Ilok process

- Wet Mechanical Beneficiation
  - Mild coal cleaning process[a]
  - Deep coal cleaning process[b]
  - Froth flotation processes
    - General type
    - USBM two-stage process
  - Multistream coal cleaning system
  - The Otisca process
  - Wet high-gradient magnetic separation process
  - NRCC oil agglomeration process

CHEMICAL COAL BENEFICIATION PROCESSES

- TRW-Meyers coal desulfurization process
- Battelle hydrothermal coal process
- PERC sodium hydroxide beneficiation process
- SURC chemical comminution process
- Ledgemont oxygen leaching process
- KVB sulfur oxidation process
- PERC oxidative desulfurization process
- ARCO process
- JPL low-temperature chlorinolysis process

MICROBIAL COAL BENEFICIATION METHODS

- Bacterial desulfurization process

---

[a] This corresponds to what is generally understood in the trade to be a level 2 cleaning operation. Generally, at this level, the ROM coal is crushed to a suitable size (5 in. x 0) and separated into a coarse coal (5 in. x 1/4) and a fine coal (-1/4 in. x 0) fraction. The coarse coal fraction is wet beneficiated (using jigs, screens, and centrifuges), while the fine coal fraction bypasses the washing operations. The two size fractions are then combined downstream of the washing plant for sale as plant product.

[b] This corresponds to what is generally understood in the trade to be a level 4 cleaning operation. It involves more thorough beneficiation of the coal. Generally at this level, the ROM coal is crushed to 1-1/2 in. x 0 and then wet screened (deslimed) at 28 mesh (Tyler standard screen size). The 1-1/2 in. x 28 mesh (M) size fraction is then thoroughly cleaned (often using heavy-media cleaning), while the 28 mesh x 0 size fraction is cleaned in froth flotation cells. The cleaned coal is subsequently combined and may be dried in thermal dryers (depending on the product coal specifications desired) prior to shipment for sale as plant product.

Table 1.2. Representative U.S. coals selected as basis for coal beneficiation studies[a]

Coal region	County	Bed	Rank	Proximate analysis (wt %), wet basis				Ultimate analysis (wt %), dry basis						Heating value, HHV (Btu/lb), maf basis	Hardgrove grindability index, HGI
				Moisture	Fixed carbon	Volatile matter	Ash	C	H	O	N	S[b]	Ash		
Pennsylvania	Somerset	Lower Kittanning	Bituminous	1.5	55.1	16.5	26.9	60.7	3.92	3.98	1.2	2.9 PY = 2.46 O = 0.44	27.3	15,194	94
West Virginia (Northern County)	Kanawha	Winifrede	Bituminous	3.2	73.6	18.1	5.1	81.3	4.6	6.94	1.1	0.66 PY = 0.07 O = 0.59	5.4	14,916	43
West Virginia (Southern County)	Logan	Lower Kittanning	Bituminous	2.1	68.1	16.7	13.1	72.7	4.5	7.7	1.09	0.61 PY = 0.09 O = 0.52	13.4	14,747	39
Western Kentucky	Hopkins	Coal Bed 6	Bituminous	1.8	47.7	35.6	14.9	66.96	4.87	9.2	1.22	2.55 PY = 1.69 O = 0.86	15.2	14,367	53
Illinois	Williamson	Coal Bed 6	Bituminous	1.9	44.5	35.7	17.9	61.06	4.88	10.35	1.25	4.21 PY = 2.58 O = 1.63	18.25	13,877	60
Wyoming	Sweetwater	Rock Springs No. 11	Subbituminous	11.2	46.3	37.0	5.5	68.22	6.19	17.33	1.1	0.96 PY = 0.23 O = 0.73	6.2	13,408	51
Wyoming	Carbon	Johnson	Subbituminous	15.6	41.1	35.8	7.5	65.75	5.01	18.65	1.14	0.56 PY = 0.08 O = 0.48	8.89	12,470	
North Dakota	Mercer	Dakota Star (Mine)	Lignite	35.8	30.7	27.4	6.1	60.2	5.3	23.3	0.9	0.8 PY = 0.55 O = 0.25	9.5	11,537	
North Dakota	McLean	Garrison Creek	Lignite	38.9	29.5	27.1	4.5	60.5	6.3	24.1	1.4	0.3	7.4	11,901	

[a] Information obtained from refs. 1 and 2.

[b] PY = pyritic sulfur. The pyritic sulfur indicated includes the sulfate sulfur present in the coal.
O = organic sulfur.

In the present study, the representative coals were screened to determine which coals would be more attractive from a beneficiation viewpoint. This subset of representative coals consists of the following:

1. Pennsylvania coal — a bituminous coal from the lower Kittanning coal seam located in Somerset County, Pennsylvania;
2. Western Kentucky coal — a bituminous coal from coal bed No. 6 located in Hopkins County, western Kentucky; and
3. Illinois coal — a bituminous coal from coal bed No. 6 located in Williamson County, Illinois.

These coals were selected from the coals given in Table 1.2 principally because of their high sulfur content. The remaining coals in Table 1.2 — namely, the West Virginia, Wyoming, and North Dakota coals — can be burned either directly (without exceeding the EPA emission limit of 1.2 lb SO_x per million Btu) or after being subjected to a wet beneficiation process. Further information on the beneficiation of these latter coals is presented in Sect. 1.4.

1.2.3 Basis of information

Information regarding the candidate coal beneficiation processes was obtained either directly from the process developers, from the equipment manufacturers, or from open literature sources. No proprietary information was obtained.

1.2.4 Analysis procedure

The analysis of the candidate beneficiation process was conducted based on the extent of information obtained about the process. Generally, much more information was available for existing coal beneficiation methods (such as physical coal cleaning) than for several of the more esoteric chemical and microbial coal beneficiation methods. All of the chemical and microbial beneficiation techniques discussed in this report are at various stages of process development, some being at a more advanced stage than others. This is not intended to imply that physical beneficiation processes are not being developed; on the contrary, several novel physical coal cleaning methods are under development.

The analysis procedure for each candidate process generally consisted of a (1) brief overview of the process, (2) detailed evaluation of the process, and (3) conclusions and recommendations regarding the process.

Contingent upon the availability of information and time, the detailed evaluation of the process consisted of developing all or part of the following information regarding each candidate process:

1. detailed process description;
2. block flow diagrams and process flowsheets;
3. feed, product, and effluent compositions and their quantities;
4. energy balances;
5. economic summary, including capital and annual operating costs together with estimates of their accuracy;
6. development status summary;
7. special materials of construction (if required) and their fabrication and construction considerations;
8. problem areas of the process;
9. environmental considerations;
10. regional considerations;
11. additional data that may be required to upgrade the quality of the technical and/or economic evaluation presented; and
12. conclusions regarding the process and, if warranted, recommendations to speed the completion of its development.

The mass and energy balances and the economic evaluations indicated in items 3, 4, and 5 above were developed for two conceptual plant sizes and for two types of installations. The conceptual plants were designed to produce 1500 and 15,000 tons/day of maf product coal. In addition, both a grassroots facility and a battery-limits facility were designed. The premised plant sizes and types of facilities were developed by ERDA/Fossil Energy, Office of Program Planning and Analysis (now a part of the Department of Energy).

1.3 Basic Premises

The following basic premises were developed to facilitate the study of the coal beneficiation processes:

1. Feed coal to the beneficiation plant was premised to be 24 in. x 0 size ROM coal.
2. The cleaned product coal from the beneficiation plant was taken to be the size generated by the process, provided it could be shipped without excessive wind loss. The product coal moisture content was premised to be 5%.
3. For the grassroots facility, the only inputs to the beneficiation plant were ROM coal and raw water. All utilities required by the plant were to be developed onsite.
4. For the battery-limits facility, all plant utility requirements were to be purchased.
5. All economics for the beneficiation plants were developed in terms of January 1977 dollars. No forward escalation beyond January 1977 was included.
6. Effluent streams from the plants were assumed to be in compliance with applicable first-quarter 1977 federal guidelines.
7. The conceptual plants' annual service factor was assumed to be 90% from the first year of operation and throughout the life of the plant.

Other premises required in the study (such as the premises for the economics evaluations) are listed separately in this report.

1.4 Application of Coal Beneficiation to the Selected West Virginia, Wyoming, and North Dakota Coals

The West Virginia, Wyoming, and North Dakota coals listed in Table 1.2 were excluded from the subset of coals used for the more detailed evaluation of three of the beneficiation processes primarily because of their low sulfur content. Notes on the beneficiation of these relatively low-sulfur coals are presented below.

1.4.1 West Virginia bituminous coals

The raw coals from West Virginia reported in Table 1.2 have low sulfur contents and can meet the EPA SO_x emission standards without beneficiation. These coals contain a small amount of pyritic sulfur (Kanawha County, 0.07% pyritic sulfur; Logan County, 0.09%), and very little reduction in the sulfur levels of these two coals would be achieved by beneficiating these coals using currently commercial coal beneficiation processes. However, beneficiating these coals could lower their ash content. It should be noted that these statements apply only to the West Virginia coals selected (and not to all West Virginia coals). The selected coals are found mainly in southern West Virginia.

1.4.2 Wyoming subbituminous coals

The Wyoming subbituminous coals selected are also low in pyritic sulfur, and one of the two (Carbon County, Johnson seam coal) will meet the current EPA SO_x emission standards when burned. For the other Wyoming coal (Sweetwater County, Rock Springs No. 11), washability data indicate that the sulfur content can be lowered to meet the minimum SO_x emission standards (1.2 lb SO_2 per million Btu) by wet mechanical beneficiation. However, in order to liberate sufficient quantities of pyritic sulfur for beneficiation to be effective, the coal must be crushed to 14 mesh. Coal of this fineness generally limits the type of mechanical beneficiation equipment that can be employed to various combinations of high-flow heavy medium, washing tables, water cyclones, and/or froth flotation. Since this coal is a borderline case with respect to meeting SO_x emission standards, the coal must be well characterized, complete washability tests made, crushed coal size spectrum determined, and expert attention given to the selection of the beneficiation equipment and process design. The beneficiation process selected would probably fall into the deep cleaning category providing for maximum pyritic sulfur reduction.

Assuming that the wet mechanical beneficiation process achieves the sulfur reduction goals, processing costs will be higher than those estimated for deep cleaning Pennsylvania coal. More specifically, crushing costs will be greater, and additional costs will be incurred because a larger proportion of coal fines must be cleaned and dried.

1.4.3 North Dakota lignite coals

The North Dakota lignite coals listed in Table 1.2 are from Mercer and McLean Counties. The McLean County lignite has only 0.3% total sulfur — well within EPA standards for SO_x emission — and does not require beneficiation. About 69% of the sulfur in the Mercer County lignite is pyritic sulfur. If one assumes that lignites are amenable to cleaning similar to eastern bituminous coals with comparable percentages of pyrite, this coal could be beneficiated by a mild cleaning method and quite definitely by a deep cleaning system. Unfortunately, very little data[3] has been published on the beneficiation characteristics of lignite coals.

1.4.4 Drying and transportation of western subbituminous and lignite coals

1.4.4.1 Drying. At this point it seems appropriate to review salient features of drying and transporting the dried western subbituminous and lignite coals. Considered low-rank coals, they contain from 15 to 40 wt % moisture and a small amount of sulfur. Drying these coals produces a friable material, and size degradations[4,5] occur during the process. Considerable quantities of dust are also generated, much of it -200 mesh, which must be collected and recycled. In large-scale drying tests[5] on Montana subbituminous coal, 3.7 wt % of the dry feed weight was collected as dust and 7.7 wt % of the dry feed of North Dakota lignite was collected as dust. The amount of dusting appears to be a function of the degree of drying and possibly the type of dryer employed. A variation in moisture content with coal particle size was also noted for the dried product. This aspect was much more apparent when the feed coal had a broad size spectrum.

1.4.4.2 Transportation. Due to the relatively high pyrophoric (spontaneous ignition) nature of western subbituminous and lignite coals, these coals should be cooled to ambient temperature after drying, especially if they are to be stored or shipped. Another method suggested to aid in reducing the coal reactivity is a controlled pretreatment of the dried coal with air. To provide a measure of the self-ignition characteristic of the dried subbituminous and lignite coal, the oxygen content of each coal was determined immediately after being loaded into open-top coal gondolas. The oxygen determination was made at the center of the bed with the bed at approximately ambient temperature. The initial oxygen content for both types of coals was 22%, and within 1 hr the oxygen content of the subbituminous coal bed dropped to 4%, while for the same time period the oxygen content of the lignite coal bed dropped to less than 1%.

For rail shipment, treatment of the low-rank dried coals is necessary to prevent wind loss and subsequent airborne contamination. One recommended method of treatment involves coating the dried coal with heavy oil at the rate of 1.5 to 2.0 gal/ton. In rail transport, care must be exercised to prevent air leakage through bottom unloading doors; otherwise rapid heating and combustion of the dried coals may occur.

Loading, unloading, and stockpiling operations can be accomplished with standard coal handling equipment without any apparent difficulties. In stockpiling the dried, low-rank coals, careful and thorough compaction is required to prevent air leakage into the coal pile.

Utilization of wet mechanical beneficiation methods for cleaning western subbituminous and lignite coals may or may not produce an acceptable level of sulfur in the treated coal. With many eastern bituminous coals, actual removal of pyrite by mechanical separation is determined by washability tests, and the same will apply to the low-rank western coals. Because the amount of pyrite present in these coals is small, it might be assumed that sulfur reduction achieved by mechanical beneficiation would be small, and in effect the separation would tend to be difficult. Beneficiation costs would be at least the same as, and perhaps greater than, those for beneficiating eastern bituminous coals. If eastern markets are contemplated for the western coals, transportation costs would be substantially greater on a tonnage basis (when competing with eastern coals), especially since the heating value of the western coals is less than that of the eastern coals.

2. DRY MECHANICAL SEPARATION PROCESSES

2.1 Crushing and Screening Methods

2.1.1 Crushing

In early coal mining operations, the practice was to recover as much lump coal as possible and to discard the fines. The current market demands for uniform coal sizes and the ever-increasing need for cleaner coals have necessitated crushing operations to enable the operators to meet the exacting size specifications and to facilitate subsequent mechanical beneficiation processes.

Because most of the coal being produced today is cleaned, the main objectives of crushing are to reduce the ROM coal to a size suitable for washing and, secondly, to size coal for market specifications. Size reduction involves various principles such as compression, impact, shearing, splitting, and attrition. Generally, more than one of the principles is employed in a crusher; for example, a shearing action is encountered with the main crushing principle of compression in a roll crusher.

Crushing is usually accomplished with a series of crushers, each subsequent crusher producing a finer product until the required size consist is reached. Initial size reduction is performed with primary breakers. Primary crushers are designed to receive ROM coal and reduce it to a top size of from 2 to 8 in. A bar grate or screen is usually positioned ahead of these breakers to remove undersized coal in the feed.

Included among the numerous types of primary crushers commercially available are single and double roll crushers, hammer mills, and rotary breakers. The rotary breaker, a perforated rotating drum, is the only crusher that provides some degree of beneficiation. ROM coal is fed into one end, and breakage is achieved by the lifting and dropping action of the rotating drum. Sized coal is discharged through the shell perforations, while rock and tramp iron are discharged through the refuse chute.

Secondary crushing varies considerably with the facilities that follow the primary crushing. If coal cleaning facilities are used, secondary crushers may be used to reduce the size of the middling fraction from jigs or the middling fraction from heavy-medium trough separators, and in turn these fractions would be rewashed. On the other hand, secondary reduction may be designed to reduce coal product from the primary crushers or to reduce cleaned product coal from the washing plant to the market specification.

2.1.2 Screening

In coal preparation, sizing is one of the more important functions and is found throughout the entire coal mining and processing operation. Sizing, as it refers to coal, is the separation of a heterogeneous mixture of particle sizes into groups wherein all particles range between a maximum and minimum size. Coal sizing is a beneficiation process. In the coal industry, sizing is nearly always performed by passing the coal over a screen. In today's modern coal preparation facilities, vibrating-type screens are more predominant, generally replacing older designs such as the shaker and trommel screens.

Screening operations are performed in coal operations to: (1) remove fines or undersized coal from crusher feeds to conserve power or to prevent overcrushing; (2) segregate coal sizes for feed to different types of beneficiation equipment; (3) separate heavy mediums, such as magnetite, from the coal product or refuse; and (4) separate product coal into commercial sizes. The last objective is not as valid as it once was because much of the coal currently used is pulverized before use by the consumer.

2.1.3 Tramp iron removal

Two other beneficiation methods usually thought of in conjunction with crushing and screening processes are: (1) tramp iron removal and (2) hand picking operations. The presence of tramp iron in the raw coal feed can be very costly to cleaning plants from the standpoint of damaged equipment and loss of productive operation. Tramp iron is normally removed by electromagnets positioned strategically with reference to the flow of coal to maximize the effectiveness of the magnet design.

2.1.4 Hand picking

Hand picking operations, although performed on a much smaller scale than in the past, are still used in some modern coal preparation plants. Probably the earliest form of coal cleaning, hand picking is used to remove rock, coal slack, and other foreign objects. Picking methods are usually limited to coal sized 3 in. and larger. Refuse from hand picking operations usually contains a relatively high percentage of usable coal and is generally crushed to free the coal and treated in the plant to recover the coal value.

2.2 Centrifugal Separation

2.2.1 Centrifugal separator

A mechanical beneficiation technique that uses a centrifugal-type separator in series with an electrostatic separator for removing pyritic sulfur from dry fine coals was investigated by the U.S. Bureau of Mines[6] at the Morgantown Energy Research Center, Morgantown, West Virginia. Figure 2.1 is a cross section of the centrifugal separator. Finely pulverized coal (70% -200 mesh) is fed through a hollow central pipe onto a rotating disc which disperses the coal horizontally into an upward flowing airstream. Particles light enough to be entrained by the airstream are transported upward into the centrifugal fan separator. In this section, the pyrite-rich or heavier particles are propelled to the inside separator wall and fall to the heavy-particle exit where they are combined with the material that was not entrained by the airstream. Those particles sufficiently lightweight to remain suspended are carried into the annulus between the inner and outer cones of the separator. Here they are disengaged from the airstream and fall to the lightweight product exit.

The heavy-product material is recycled to the centrifuge and reprocessed at a higher air velocity than used in the initial pass. The lightweight material separated during the second step is combined with the lightweight material from the initial separation. The process is repeated, possibly three or four times, until about 75% of the -200 mesh material present in the coal feed has been collected in the lightweight fraction.

ORNL DWG 77-652

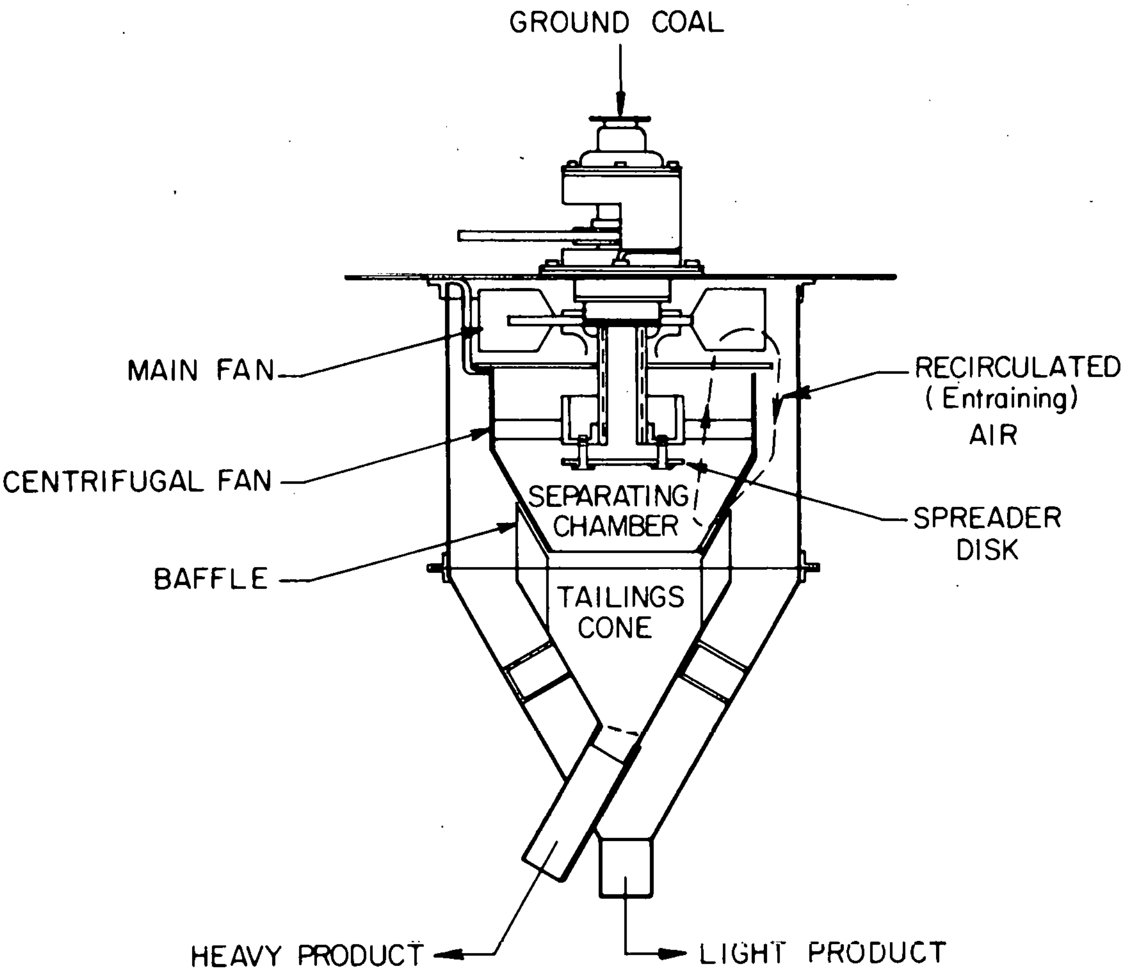


Fig. 2.1. Diagrammatic sketch of centrifugal separator.

The lightweight product from the centrifugal separations, depleted in pyritic sulfur, is taken as product and may amount to as much as 50% of the raw coal feed. The heavy-product material, enriched in pyritic sulfur, is processed on an electrostatic separator to remove the pyritic sulfur.

Some factors that influence the separation efficiency of the centrifugal separator are: (1) particle size of the coal as well as pyrite, (2) particle shape, (3) mass, (4) air velocity, and (5) equipment design. From exploratory tests made with coal ground (-60 mesh x 0) in an air-swept grinding mill, tentative processing conditions and preliminary separation efficiencies were determined for the centrifugal separator. Best separation efficiencies were obtained from closely sized particle fractions, and the maximum efficiency was obtained from the 270- to 400-mesh range. Nearly 60% of the pyritic sulfur was removed from this fraction in the tests made. Separation efficiency dropped to about 15 to 20% when the particle size fraction reached the 60- to 80-mesh range. Upon examination of the 400 mesh x 0 particle size range, it was determined that only 5% of the pyrite was separated. The explanation given for the low separation was that the pyrite was ground extremely fine in the air-swept grinding mill before it could escape with the air sweep. Another possible explanation is that the 400 mesh x 0 fraction may have contained much of the ash-forming minerals with specific gravities near that of the pyrite, and little or no separation occurred in the centrifugal separator.

2.2.2 Electrostatic separator

The heavy, pyrite-rich coal fraction from the centrifugal separator is spread in a thin layer over an electrically grounded rotor. The particles pass under an active electrode and are electrically charged. The electrostatic separator utilizes the difference in conductivity or dielectric properties of coal and mineral matter (pyrite) to maintain or dissipate the induced charge. The pyrite material becomes equipotential with the rotor and falls into a hopper. The coal-rich dielectric material becomes firmly attached to the rotor, while the intermediate material is less strongly attached and is positioned somewhat further from the rotor surface. Scraper blades set at appropriate positions with respect to the rotor remove these materials, and they fall into separate hoppers.

The most efficient single-pass pyrite separations were achieved on particles with a narrow size range, and it was determined that the most effective operation conditions (rotor speeds and voltage) were considerably different for fine and large particles. Humidity and coal moisture content have an appreciable effect on the separation, as do combinations of humidity, moisture content, and coal fines. These factors must be controlled to obtain good separation.

2.2.3 Centrifugal-electrostatic separation results

The separation results achieved by the dry separation process (centrifugal and electrostatic processing in series) on three Pittsburgh seam coals ground to 70% -200 mesh are summarized in Table 2.1. Figure 2.2 is a schematic diagram of the dry separation process.

Two types of grinding mills were used to prepare the raw coal feed for the test program — a ball mill and a Hardgrove mill. Grindability tests performed in these mills on the different coals indicated that a somewhat finer particle size is produced by the ball-milling operation.

Dry-separation beneficiation of the coals prepared in the two mills by single-stage grinding showed small differences in the percentages of pyrite extracted. Approximately 60 to 70% of the potentially available pyrite was removed. Results for stage grinding and intermediate dry separation showed significant improvements in the pyrite separation efficiency for the coals from both mills. With this latter processing method, about 85% of the potentially available pyrite was extracted.

The dry separation process for coal beneficiation is limited to the removal of pyritic sulfur from coals (as is the wet mechanical beneficiation process). The pyritic sulfur removal efficiencies are a little lower than for wet mechanical separation methods. Probably a more realistic comparison for the dry process pyrite separation efficiency would be with a froth flotation system processing the same size range of coal fines. The separation efficiencies for these two sulfur removal systems are about equal, and both perform an effective separation.

Table 2.1. Experimental results of dry separation process showing amount of pyrite removal[a]

Coal	Percent initial sulfur in coal		Pyrite removed (%)	Potential amount of pyrite available for removal (%)[b]	Pyrite in reject fraction (%)
	Total	Pyrite			
Pittsburgh seam roof coal	4.10	1.93	36[c]	50	13
Pittsburgh seam roof coal	4.10	1.93	45[d]	55	23
Pittsburgh seam utility coal	3.42	1.79	55[c]	80	20
Pittsburgh seam strip mine coal	2.98	1.87	50[c]	70	14
Pittsburgh seam utility coal	3.42	1.79	55[e]	82	22
Pittsburgh seam strip mine coal	2.98	1.87	40[e]	68	15
Pittsburgh seam strip mine coal	2.98	1.87	65[f]	74	26

[a] Information obtained from ref. 6.

[b] The potential amount of pyrite available for removal was determined by sink-float testing at 1.6 specific gravity. Sink-float tests were made on pulverized samples of the listed coals.

[c] Ball milled 60 min.

[d] Ball milled and separated in stages — 60 min total milling time (three stages).

[e] Hardgrove milled 30 min.

[f] Hardgrove milled and separated in stages — 75 min total milling time (four stages).

ORNL DWG 77-655R

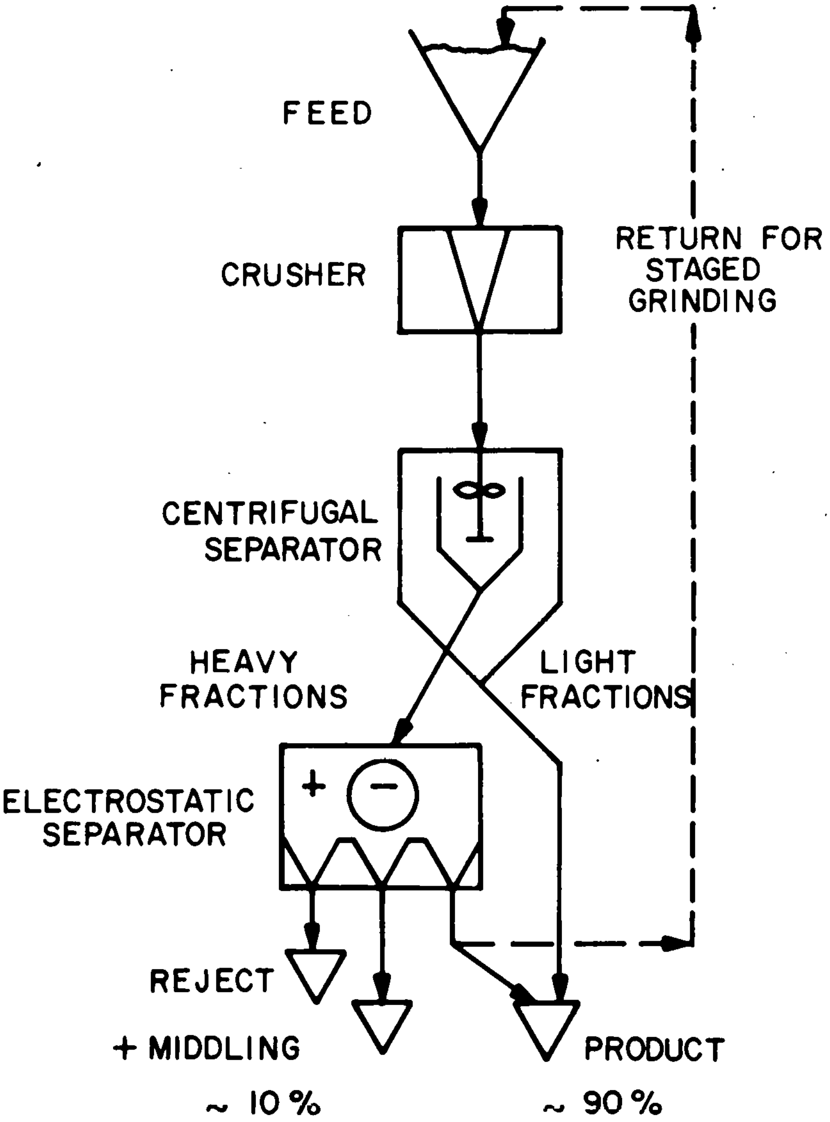


Fig. 2.2. Schematic diagram of the dry separation process.

Thermal efficiency for the dry separation process could not be determined because no heating values were given for the coal feed, product coal, or the waste material.

Commercial-scale equipment for a dry separation system would involve the development of large-scale dry centrifugal and electrostatic separators. Because of the explosive characteristics of fine coal dust, special emphasis would be needed in designing the equipment and facility, as well as in the operation of the facility. This is especially true for the electrostatic separator where a potential arcing hazard would be always present.

Commercial equipment is available for crushing, pulverizing, and coal storage operation. However, precautions must be taken in selecting the grinding equipment. This grinding should preferably be conducted in an inert atmosphere; for example, CO_2 or N_2 could be used as a blanket gas in the crushing and pulverizing operations. Ball milling and Raymond-type pulverization are preferable to impact-type equipment to minimize sparking within the equipment. Usually coal pulverization is performed at an elevated temperature (150 to 190°F); hence the associated moisture is in vapor form and does not present any problem. Storage of the fine moisture-laden coal may pose a problem in the dry separation process because serious coal caking can occur if the temperature is permitted to drop and the vapor condenses as surface moisture.

Not necessarily unique to the dry separation process, but nonetheless of considerable importance, is the rigid control of the fine coal dust that would always be present in this system. Dust control must be exercised for three important reasons: (1) to prevent a health hazard to personnel, (2) to prevent air pollution, and (3) as mentioned earlier, to prevent an explosion or fire hazard.

The transportation of the fine coal would be accomplished by using a pneumatic system which is technologically well developed. For long-distance transportation, the fine coal would have to be hauled in tank-type vessels equipped for pneumatic loading and unloading. Due consideration must be given to transporting the fine coal because of the potential hazard of tank rupture in the event of an accident. In such a case, the possibility of sparks in close proximity to the fine coal would be great and could ignite the coal.

Wastes from the facility would consist mainly of ash-forming minerals, a small amount of fine coal, and the pyrite. The pyrite is not expected to exceed a maximum of 10 to 12% in the refuse stream. It would be necessary to wet and cover this waste because of its extreme fineness; otherwise wind-blown air pollution and ground contamination would become a problem.

In summary, more laboratory-scale and small-scale pilot-plant development work is required for the dry coal beneficiation process so that thermal efficiencies, cost data, equipment scale-up factors, and more information on the potential hazards can be determined.

2.3 Dry Magnetic Separation Techniques

2.3.1 The Magnex process

The Magnex process is a dry, low-intensity magnetic beneficiation technique that uses iron carbonyl [$Fe(CO)_5$] to separate the coal from the attendant pyrites and mineral matter. The process was developed by Hazen Research, Inc. (which holds the patent for the process) under funding from Inex Resources, Inc., of Denver, Colorado. Information about the process was obtained from a paper presented by Kindig and Turner,[7] who reported on the process based on their bench-scale studies. According to these investigators, a continuous pilot plant based on the Magnex process was scheduled to start up in September 1976. Funding for the pilot plant is being provided by Inex Resources, Inc. Results of the pilot-plant studies are expected to be published soon.[8]

Figure 2.3 is a block flow diagram of the Magnex process. The process basically consists of treating pulverized coal [preferred particle size: -14 mesh (-1.4 mm)] with iron carbonyl vapor at atmospheric pressure and 338°F (170°C). The iron carbonyl decomposes to form magnetic materials on the ash and the pyrites, but it does not render the coal particles magnetic. The treated coal is then subjected to a conventional low-intensity magnetic separator where the ash and the pyrites are removed from the coal. The clean coal and the ash report to separate collecting bins.

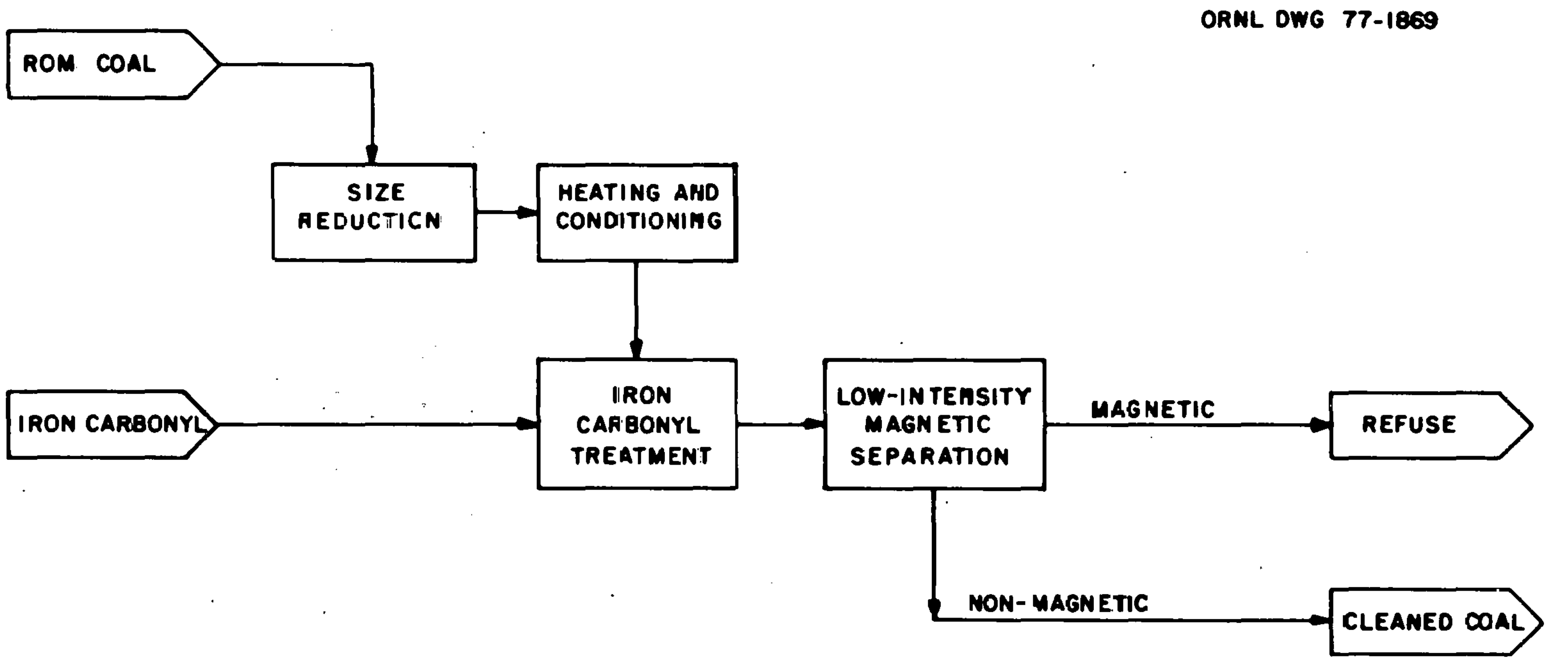


Fig. 2.3. Block flow diagram of the Magnex process.

The process is reportedly able to reduce the pyritic sulfur and ash contentsof the coals treated (Lower Freeport and Pittsburgh seam coals) by around 86 and 67%, respectively, while recovering around 73% of the clean coal. These results were obtained from the bench-scale studies conducted on the two coals. In addition, Kindig and Turner[7] report that a preliminary cost estimate for a commercial version of the process places the capital costs at around $4 per ton and the operating costs at around $6 per ton. These costs appear to be too low. However, a more detailed evaluation of the process and its economics would be required to determine more realistic cost estimates for the process.

One of the major advantages of the process as a coal beneficiating technique is that dewatering costs are eliminated and the processing scheme is relatively simple. The major disadvantage of the process is that it uses iron carbonyl to beneficiate the coal. Iron carbonyl is a highly toxic [the threshold limit value (TLV) for iron carbonyl in air is 10 ppb[9]] and relatively expensive (10¢ per pound[8]) reagent.

The process is still at an early stage of development. Although it appears to offer a relatively simple means of beneficiating coal, the use of iron carbonyl as the reagent may pose a problem in the potential commercial application of the process.

2.3.2 Dry high-gradient magnetic separation technique

The dry high-gradient magnetic separation (HGMS) technique is a process whereby the coal is beneficiated by subjecting it in a finely pulverized form to a high-intensity magnetic field [field intensity up to 20 kilo-oersteds (kOe)]. The process is similar to the wet HGMS (see Sect. 3.7) except that (1) no water is used in this process and (2) the magnetic field is applied to an air-fluidized bed of the coal particles rather than a water slurry.

The technique is currently being developed jointly by Oak Ridge National Laboratory and the Chemical Engineering Department at Auburn University.

The laboratory-scale process essentially consists of subjecting a fluidized bed of coal particles to a high-intensity magnetic field. The coal is fluidized by air inside a specially shaped container which is enclosed in an electromagnet. A magnetic separator matrix composed of several metallic screens and spacer rings is located in the container to trap the pyrites and the ash constituents. The particle size is generally in the 100- to 200-mesh (74- to 147-μm) size range. Early experimental runs indicate[10] that, by using a recirculating-type fluidized bed and a magnetic field intensity of 20 kOe, the pyrites and the ash content of the coal were reduced by about 87 and 52% respectively. Coal yields in these runs were around 80%.

The development of the process is at an early stage, and sufficient information has not been developed to assess its commercial viability. However, the technique appears to have promise, and further studies are envisaged. The major advantage of the process is that no water is involved in the beneficiation process, thereby reducing the problems associated with the dewatering of the fine coals. However, the use of an air-fluidized bed of finely pulverized coal may pose a potential explosion hazard unless appropriate steps are taken to prevent the buildup of static electricity in the bed.

2.4 Dry Table Separator

The dry table separator is a dry coal beneficiating device in which the coal is separated from the associated pyrites and mineral matter by using vibratory and gravitational forces. The equipment has been developed by FMC Corporation and was reported on by Wilson[11] in 1977.

Figure 2.4 is a sketch of the dry table separator. A cross-sectional view of the table is also shown in Fig. 2.4 to illustrate the movement of the coal and the mineral matter as they travel along the length of the table. The dry table relies on several physical properties of the coal and the mineral matter particles to effect the separation, notably the particle size, density, resiliency, and surface roughness characteristics. Basically, the dry table consists of a short but wide deck that is slightly inclined. A downward sloping surface called the discharge lip is attached to the discharge end of the deck. The deck itself is tapered along its length from the feed entry end to the mineral matter discharge end. The

ORNL DWG 77-1867

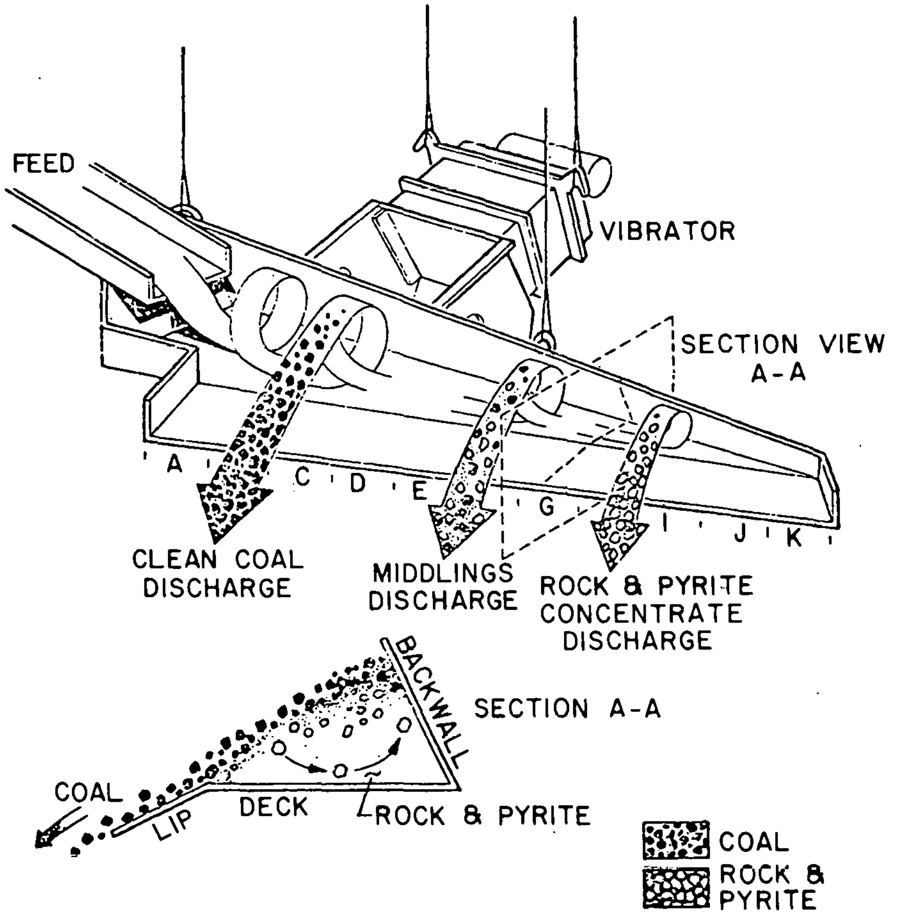


Fig. 2.4. Diagrammatic sketch of the dry table separator.

entire assembly is vibrated by an electromechanical device similar to that used in vibratory feeders.

Dry, sized raw coal is fed at the widest end of the dry table deck. For optimal coal--mineral matter separation per pass, the ratio of the top to bottom size of the feed particles should be 4 to 1. The vibrating motion of the deck causes the incoming feed particles to move toward and accumulate along the back wall of the deck. Gravity and vibratory forces make the particles on the pile surface move toward the tapered end of the deck, while at the same time the underlying material in the pile is forced toward the back wall of the deck. Also, because of the motion of the table, particles at the top of the pile are continuously discharged onto the discharge lip. Particles that are large and of low density (such as coal) tend to move to the top of the pile, from which point they are discharged onto the discharge lip; more dense particles (such as mineral matter) tend to concentrate and move along the back wall to the mineral matter-and-pyrite discharge end.

Further separation of the coal and the mineral matter occurs on the discharge lip; the degree of separation is based on the shape, resiliency, and surface roughness characteristics of the particles. Coal particles with higher resiliency and less surface roughness tend to bounce or slip off the discharge lip, whereas the less resilient and rougher mineral matter and pyrites are conveyed back up the discharge lip to the pile on the deck. These particles are ultimately discharged at the tapered end of the deck.

The quality of the discharge along the length of the dry table is similar in character to that obtained from a wet concentration table; that is, it is graded from an essentially mineral matter--free coal product (discharged close to the feed end) through a series of coal--mineral matter fractions (discharged along the length of the table) to essentially a mineral matter--pyrites product, which is discharged at the end of the deck.

Results of experimental studies reported by Wilson[11] indicate that, when the dry table separator was used to beneficiate a 4:1 sized raw Arizona subbituminous coal, 74% of the ash and 50% of the pyrites were removed from the sample coal while recovering 90% of the coal's potential heating value. However, it should be remembered that the extent of pyrite reduction obtained is generally a function of the extent of pyrites liberated during the pulverization of the feed coal and the difference between the physical properties of the coal and the pyrite particles.

The dry table separator has a beneficiation capability similar to that of a Baum jig. It can be used over a broad span of particle sizes; there are apparently no limitations on the maximum particle size that can be beneficiated. However, the minimum particle sizes that can be beneficiated are limited by the formation of agglomerates, which may be caused by a buildup of electrostatic charges or surface moisture.

The dry table separator should be regarded as a "roughing" device that can be especially useful if the availability of water is restricted and if wet beneficiation methods cannot be used.

2.5 The Ilok Process

2.5.1 Introduction

The Ilok process is a dry coal beneficiation process in which all of the sulfur (pyritic, sulfate, and organic) and the ash is removed by mechanically grinding the coal in a specially designed reductor mill down to -4-μm particle size. The process is offered as a part of the Ilok coal powder technology[12] by Dr. V. Stephen Krajcovic-Ilok. Definitive information on the process is scarce and is supposedly available from Ilok upon signing nondisclosure agreements with him. To develop the information for this report, other sources of information (in addition to the information provided by Ilok) were consulted, namely:

1. An executive summary[13] issued by EPRI based on the report submitted to them by E. E. Soehngen, an independent consultant. EPRI retained Soehngen to search into the basis for the coal cleaning technology proposed by Ilok.
2. A report by Soo and Rieber[14] based on their evaluation of the Ilok process. The evaluation of Soo and Rieber was funded by the Office of Coal, Federal Energy Administration.

The process as proposed by Ilok[12] consists of pulverizing the coal in a specially designed high-performance comminution mill conceived by Hans Rohrbach in Germany during the late 1930s. The feed coal is pulverized so that 97% of the coal consists of particles less than 4 μm in size. With coal particles at the -4-μm size, the ash and all forms of the sulfur are mechanically separated in the reductor mill. The liberated sulfur supposedly leaves the mill as H_2S. The process was estimated to require 25 kWhr/ton of coal[12] to achieve the above size comminution. Information about the process is veiled in secrecy by Ilok, who supposedly holds the patents to the process.

2.5.2 Conclusions and recommendations

The following conclusions may be made regarding the Ilok process, based on the information available:

1. The process appears to be of dubious merit. Soehngen[13] indicated that the process is based on conceptual theories propounded by Hans Rohrbach; no plant utilizing the process has ever been built. In his evaluation of the basis of the process for EPRI, Soehngen reports[13] that he was not able to find facts to substantiate the claims made by Ilok.

2. Soo and Rieber[14] state that, based on the information supplied to them by Ilok under a nondisclosure agreement:

   a. The process will not work.

   b. The coal input to the reductor mill is not ROM coal but highly cleaned, carefully sized nut coal.

   c. Even supposing that such a micropulverizing mill worked, the power requirements for the above comminution level, based on accepted physical principles, would not be less than 200 kWhr/ton of coal. This value is several times the value estimated by Ilok.

It is recommended that no further effort be expended on an evaluation of the Ilok process, at least until substantive evidence to support the claims of this process is presented.

3. WET MECHANICAL SEPARATION METHODS

3.1 Introduction — Wet Mechanical Beneficiation

Historically, wet cleaning of coal to lower the ash and sulfur contents was practiced by coke producers as far back as the last century. Today, in excess of 45% of the bituminous and anthracite coals are mechanically cleaned, whereas only very small tonnages of subbituminous coals and practically no lignite coals are so cleaned.

Wet mechanical beneficiation methods generally employ gravity concentration for preparing cleaned coal; the one exception is froth flotation. Wet cleaning methods are limited to the partial removal of ash and pyritic sulfur contents of the coals. The effectiveness of the washing process is dependent upon the particular physical characteristics of the coal. These characteristics determine the ease or difficulty with which the impurities can be liberated from the coal. Some of the physical properties affecting separation are: (1) specific gravity of impurities, (2) coal fracture system, (3) size composition, (4) hardness, (5) grindability, and (6) distribution and particle size of the pyritic sulfur.

In the past three or four decades, development of cleaning technology and improvements in wet beneficiation equipment have accelerated greatly. Introduction of continuous mining and full seam mining methods has markedly increased the ash and sulfur levels of the ROM coal and has placed greater emphasis on cleaning plants.[15] Rapidly changing coal markets — that is, the demand for a more uniform coal product in the fine sizes as well as in the coarse sizes and the coal producer's drive for increased profits — have contributed to the growth of coal preparation technology and improved equipment designs. Additionally, new state and federal laws aimed at eliminating pollution have been enacted. These regulations have influenced coal producers to improve waste-treatment facilities, to improve or develop new fine coal recovery systems, and to provide additional equipment for recycling water supplies as a conservation measure as well as for elimination of stream pollution.

Various types of wet beneficiation equipment are commercially available from coal equipment manufacturers. A summary of the more generally used wet mechanical cleaning equipment is presented in Table 3.1.

Table 3.1. Wet mechanical beneficiation equipment

- For coarse coal (8 x 1/4 in.) processing
  - Dense-medium equipment
  - Jigs
- For fine coal (-1/4 in. x 0) processing
  - Dense-medium cyclones
  - Water only cyclones
  - Wet concentration tables
  - Froth flotation
  - Centrifuges

The equipment listed in Table 3.1 is available in numerous designs and capacities to handle essentially any coal cleaning problem. Modern cleaning facilities usually have several types of cleaning equipment designed into the process to effect a more efficient separation. The cleaning equipment is augmented with a large array of commercially available crushing, grinding, sizing, conveying, dewatering, drying, and storage equipment of comparable capacities.

Wet mechanical cleaning processes are limited to partial removal of the pyritic sulfur (about 25 to 65%) and to the lowering of ash impurities present in the coal. The reduction of these constituents is dependent on the physical characteristics of the coal feedstock. In recent years most of the research and development efforts in wet mechanical cleaning methods have been directed toward lowering the sulfur content of coals. To this end, the top size of coal to be cleaned has been reduced, as required, to liberate more of the impurities. Not only is more sulfur removed, but several basic changes have taken place in the plant designs. First, greater emphasis has been placed on dense-medium separation-type equipment and, subsequently, more tabling and/or froth flotation circuits are needed to maintain process efficiencies and to handle the increased percentages of the fine coal. Also, as the percentage of fine coal increases, the coal-drying requirements are proportionally larger. Each of these changes produces an incremental increase in the coal processing costs. With the incentives mentioned earlier, equipment manufacturers and coal producers have increased equipment capacities, improved separation efficiencies, and minimized production costs. The greatest advancements in wet mechanical cleaning technology have been achieved in fine-coal processing and recovery. However, in the overall wet mechanical cleaning technology, the area of fine-coal preparation still has the greatest potential for improvements in processing efficiencies and operating costs.

3.2 Wet Mechanical Beneficiation Equipment

3.2.1 Jigs

The basic principle of jigging is that the pulsating fluid flow through a bed of coal causes expansion and compaction of the coal bed. A stratification of the raw coal results in which the density of the bed increases from the top to the bottom. Water is normally used and is pulsated with air or with plungers. Most jigging operations being installed today have fixed screens for coal bed support and are air actuated. The jigs are available in a variety of designs for separating two or more products and have the ability to handle raw coal feeds up to 8 in. in size. Depending on the feed coal size, the capacity of jigs ranges up to approximately 1000 tons/hr. The capacity range for jigs is about 3 to 6 tons/hr of coal per square foot of effective washing area. For example, a jig with about 180 ft^2 of effective washing area can process about 1000 tons/hr of 6-in. x 0 size coal.

Most of the coal mechanically cleaned in the United States is washed in jigs because operating costs for jigs are somewhat lower than for other processes. In comparison with the highly effective dense-medium separation equipment, jigs are slightly less effective in achieving both quality and high recovery, especially when processing raw coal feeds containing a high percentage of "near-gravity" material.

3.2.2 Wet concentration tables

The wet concentration table is one of the oldest coal cleaning devices. The capacity of the table depends on feed coal size and washability characteristics. Single-deck wet vibrating tables (134 ft^2 in size) will effectively process up to 10 tons/hr of 3/8 or 5/16-in. x 0 size feed. Coal sizes up to 1-1/2 in. x 0 can be processed using wet concentration tables at rates of about 15 to 25 tons/hr per table. In many cases, double-deck concentration tables are used to effect a better separation.

In operation, raw coal is spread over the table deck by the externally induced vibrational motion, and gravitational flow stratifies the particles behind riffles on the table. Cross-flowing water removes successive layers of the stratified particles from the top downward as the coal bed travels toward the outer end of the table.

3.2.3 Water-type cyclones

Water-type cyclones (hydrocyclones) are used to clean 1/4-in. x 0 size coals, using water as the transport fluid. The water cyclone[16] is a cylindrical vessel with a conical-shaped bottom section and a tangential inlet near the top. The water cyclone differs somewhat from the conventional dense-medium cyclone in that the cone angle is larger (up to 120°) and the internal vortex finder is longer. A coal-water slurry is fed to the tangential feed nozzle and, upon entering the cyclone, is subjected to centrifugal forces. The lighter-density coal particles are generally retained by the ascending vortex and exit through the overflow. Conversely, the higher-density mineral matter tends to migrate to the descending vortex and reports to the underflow. Treatment of -1/4-in. coal in hydrocyclones often results in significant crossover of clean coal to the refuse stream, which necessitates a two-stage system or one followed by a flotation unit. Sharp separations are not obtained in hydrocyclones, and they cannot be used for difficult-to-clean coal, for separations at the lower specific gravities, or with fine coals containing a large percentage of "near-gravity" material. Hydrocyclones find application in treating feeds with appreciable concentrations of liberated pyrite or where space limitations are important.

3.2.4 Low-flow dense-medium vessels

The dense- (heavy-) medium separation process usually treats coal from 8 in. down to 1/4 in. in size by submerging the raw coal into a liquid suspension that has a specific gravity intermediate between the coal and the mineral impurities. The coal floats and the waste material sinks in the liquid. Liquids in the form of organic liquids or salts dissolved in water find limited use in commercial practice because of high costs of recovery of liquids from the coal and waste products. Several different equipment designs are available for dense-medium separation, and all use the same principle wherein the product coal floats and the waste material sinks.

Of the suspension materials employed in dense-medium separation (sand, bauxite, ferrosilicon, and magnetite), magnetite is most frequently used because of its low cost (approximately $70/ton for -325-mesh magnetite) and the ease with which it can be recovered by magnets. Magnetite losses amount to 1.5 to 1.75 lb of magnetite per ton of coal treated. For coarse coal, the present design trend in dense-medium separation equipment is toward shallow baths (settling tanks) where an inactive or low-flow region is provided for the separation to occur. Shallow baths minimize the amount of magnetite required in the system. Today's modern dense-medium processes are capable of very high throughputs (up to 850 to 900 tons/hr of coal feed) and effect a sharp separation of the feed coal into a clean product and refuse. They are highly automated and require a very small operating crew.

The advantages of dense-medium processes over other coal beneficiation processes are: (1) the ability to make sharp separations within the normal specific gravity range even at high percentages of near ±0.1 specific gravity material; (2) the ability to easily control the specific gravity of the dense medium to within ±0.005 specific gravity unit of the separating gravity; (3) the flexibility to change the specific gravity of the medium to meet product requirement as well as raw coal feed; (4) the ability to handle a wide range of raw coal sizes up to 8 in.; and (5) low capital and operating costs, considering the high coal throughput and the small area required for the separation.

3.2.5 High-flow dense-medium vessels — cleaning of 2 in. x 28 mesh coal

One of the simplest and yet one of the most effective devices for beneficiating coal is the heavy-medium cyclone. Presized coal ranging from 2 in. down to 28 mesh is premixed with the heavy medium and fed to the cyclone at pressures up to 25 to 30 psig. In a typical heavy-medium cyclone, a mixture of medium (usually magnetite) and deslimed raw coal (that is, coal from which the -28 mesh material has been removed) enters tangentially near the top of the cyclone section. In the cyclone, the normal gravitational force found in a heavy-medium static bath is replaced by a much stronger centrifugal force. Due to strong centrifugal action, the clean coal (being of lower specific gravity) is forced toward the axis of the cyclone while the mineral matter (being of higher density) is forced toward the walls of the cyclone. Hence, the clean coal is separated from the associated mineral matter. The clean coal collected at the central axis of the cyclone passes through a vortex-finder (a concentric tube located about the cyclone axis) and exits the cyclone at the top while the mineral matter is discharged (through an underflow orifice) from the bottom of the cyclone.

As a consequence of the high separating forces developed in this type of fine-coal separator, cyclones are very compact in size but have high capacities and are even able to clean fine coal at these high throughputs.

The heavy medium used in the cyclone acts as a homogeneous fluid because of the fine particle size employed (generally 95% through 325 mesh), and significant separation of the magnetite particles from the water does not occur. The heavy medium flows out of the cyclone with both the cleaned coal and the mineral matter stream and is recovered (for re-use) from both streams downstream of the cyclone.

Both the cyclone overflow and underflow pass over sieve-bend screens and then over wash and drain screens to remove nearly all the heavy medium from the cleaned coal and the waste materials. Capacities of dense-medium cyclones, for example, range up to 100 tons/hr for 28-in.-diam units, and cyclones can handle coal sizes ranging from 28 mesh to 2 in. For the 2-in. to 28-mesh size coal range, the cyclone performs a sharper separation between the coal and refuse than any other type of separator that is commercially available. Capital and operating costs are usually higher for dense-medium cyclone installations than for comparable hydrocyclones or vibrating-table systems. However, with their superior separation capabilities at low operating densities, dense-medium cyclone operations have a decided economic advantage over other types of fine coal separation systems, especially if a large amount of "near-gravity" material is present in the coal feed.

The original development work on dense-medium cyclones was performed by the Dutch State Mines during World War II. Since then, dense-medium cyclones have been used commercially in Europe (notably in Holland, Germany, and France). The first commercial application of the dense-medium cyclones in the United States was in 1961. Several preparation plants have since been built which use dense-medium cyclones in the coal preparation circuit.

Because dense-medium cyclone systems made their entry into this country's coal cleaning industry fairly recently, more developments and improvements will undoubtedly be made. For example, within the past five or six years, the top size of the feed has been increased to 2 in. and, except for the -28 mesh x 0 material, the entire plant throughput can be cleaned in dense-medium cyclones.

The major problem with dense-medium cyclone separation is that it cannot effectively treat -28 mesh coal. A separate fine coal treatment circuit is required for this purpose. Several coal cleaning plants are now using froth flotation circuits to handle coal fines. However, based on recent development work at the U.S. Bureau of Mines,[17] the effective range of the heavy-medium cyclone may be extended to include the 48 mesh x 0 fines. In their investigations, the U.S. Bureau of Mines limited the raw coal feed size to the 48 mesh x 0 material. Normally, this size fraction of the raw coal contains the greater percentage of clay and slimes (as well as some of the pyrite) and is the most difficult fraction to beneficiate. The clay and slime associated with the raw coal report in this size fraction because of their fine particle size. The U.S. Bureau of Mines studies showed excellent separation of the fine coal down to 65 mesh and still good separation results in the 65- by 100-mesh range material. Therefore, the potential exists for treating the entire coal throughput by using heavy-medium cyclones.

3.3 Froth Flotation

3.3.1 General techniques

In past years, ultrafine coal along with the refuse materials was discarded because of the low coal prices and the relatively high recovery costs associated with processing fine coal. However, the influence of rising coal prices, the resulting demand for improved cost efficiencies, and the need to meet stringent environmental regulations are important factors contributing to the present emphasis on the recovery of the fine coal. Coals in the 48 mesh x 0 size range are generally cleaned by froth flotation. Froth flotation techniques are employed to separate the fine coal from the pyrites, slimes, and associated ash-bearing minerals.

Froth flotation of coal is a process that depends on the selective adhesion of air bubbles to the coal particles to separate the fine coal from the associated mineral matter. As finely dispersed air bubbles are passed through the coal slurry, the air bubbles adhere to the coal particles and float them to the surface where they are removed as a concentrate while the associated mineral matter, wetted by the water, sinks to the bottom of the vessel. This process entails the use of chemical reagents which form an air-adhering surface on the coal particles and which make a wettable surface on the ash-forming particles. In addition, flotation agents are added to the coal slurry prior to or during flotation to aid the separation process. These reagents are classified as frothers, collectors, and modifying agents.

Frothing agents facilitate the production of stable froths. A stable froth is needed to carry the coal concentrate until it can be removed from the flotation unit. The frothing agents can be inorganic or organic in nature, but most are organic materials such as alcohols, kerosene, and even crude oil.

Collector reagents aid in promoting better contact between the coal particle and air bubbles by forming a thin film over the coal particles, thus forming a water-repellant surface. However, in order to effect a separation, the collector must not coat the ash-forming or pyritic minerals.

Modifying agents serve several functions,which include: (1) dispersing agents inhibiting unwanted mineral flotation by coating the mineral particles and not coating the coal particles, (2) activating agents to alter the coal surface to enable a film coating of the collector reagent to form and aid the air-bubble attachment, (3) pH regulators to adjust the flotation slurry alkalinity or acidity, and (4) dispersing agents to help reduce the effects of slimes and clays on the separation.

Froth flotation reagents are the most expensive items in flotation processing systems, and it is imperative that the proper kind and amount of reagent be used. Reagent costs have been estimated to be 50 to 60% of the total flotation system operating cost. Even though recent developments in froth flotation techniques have increased flotation process recovery efficiencies, a continuing effort aimed at developing better and cheaper reagents should be pursued.

Coal processors and equipment manufacturers have made great strides in overall froth flotation cell technology. Continuing efforts are being made to improve cell efficiency, increase capacity, lower power requirements, and provide complete automation in order to lower operating costs. One new method being investigated involves separating the feed into specific size ranges such as 14 mesh x 48 mesh, 48 mesh x 100 mesh, and 100 mesh x 0.[18] Better cleaning efficiencies were obtained for the individual size fractions than were obtained for the overall -14 mesh size range. Other process improvements being made include froth flotation treatment of overflows from classifiers and water cyclones to decrease the load on thickeners, thus simplifying the water recycle circuits.

3.3.2 U.S. Bureau of Mines two-stage froth flotation process

Excellent pyritic separation results have been obtained in a two-stage froth flotation circuit developed by the U.S. Bureau of Mines.[19] This system is unique in that a frother [methylisobutyl carbinol (MIBC)] is used in one stage to concentrate the fine coal. The coal concentrate is then repulped and treated with a coal depressant (Aero Depressant 633) and hydrochloric acid (HCl) to which a pyrite collector (potassium amylxanthate) and a frother (MIBC) are added. In the second stage, the coal sinks and the pyrite floats to the surface, that is, the reverse of normal flotation methods. Pyrite separations of 70 and 90% have been achieved for two Pennsylvania coals.

In the future, froth flotation processing will play a more significant role in coal cleaning due to the greater amounts of fines found in raw coal produced by continuous mining methods and the need to intentionally reduce raw coal sizes to liberate more of the pyritic contents and enhance the recovery of clean marketable coal.

3.4 Preliminary Process Designs and Economic Evaluations Based on Wet Mechanical Beneficiation

3.4.1 General design considerations

Preliminary process designs and economic evaluations have been developed for conceptual coal cleaning plants that beneficiate the coal by using the wet mechanical beneficiation process. The designs were developed for plants beneficiating the Pennsylvania, western Kentucky, and Illinois coals (see Table 1.2 for details and analyses of the coals). These coals were selected from Table 1.2 because of their high sulfur content and differences in cleaning properties. To assess the effect of plant capacity and the degree of beneficiation, the plant designs were developed for two levels of product coal capacity (1500 and 15,000 tons/day of maf coal) and for two levels of cleaning — namely, mild and deep cleaning of coal.

In the mild coal cleaning plants, the ROM coal (premised to be 24 in. x 0 in size) is crushed and reduced to a 5 in. x 0 size consist.

The 5 in. x 0 coal is then dry-classified using 1/4-in. screens into two fractions: a 5- x 1/4-in. fraction and a -1/4-in. fraction. The 5- x 1/4-in. size fraction (also generally referred to in the trade as coarse coal) is then wet beneficiated using jigs. The -1/4-in. size fraction bypasses the wet beneficiation step and is combined with the cleaned and dewatered coarse coal fraction to yield the cleaned coal product from the plant.

In the deep coal cleaning plants, the ROM coal (24 in. x 0 size) is crushed and reduced in size to yield a 1-1/2 in. x 0 size consist raw feed coal. The raw feed coal is then wet-classified (deslimed) using 28-mesh screens into two fractions: 1-1/2 in. x 28 mesh and -28 mesh. The 1-1/2 in. x 28 mesh size fraction raw coal is beneficiated using two-stage dense-medium cyclones, while the -28 mesh size fraction is beneficiated using froth flotation cells. In the deep coal cleaning conceptual designs evaluated in this study, only a fraction (~66%) of the -28 mesh coal was subjected to thermal drying along with the cleaned and dewatered 1-1/2 in. x 28 mesh size coal. This step was taken so as to meet the premised 5% moisture content specified for the plant cleaned coal product. The thermally dried and undried coal streams are subsequently combined to yield the plant product coal stream.

The proposed conceptual plants will provide guidelines for establishing relative beneficiation costs for easy-to-clean and the more-difficult-to-clean coals. It is recognized that the proposed cleaning systems are not necessarily optimum because of the very limited amount of data available for the particular coals. The available data were restricted to coal analyses, heating value, and a minimal amount of washability information. Other essential data that are valuable in designing a cleaning process include mining techniques,[15] raw coal and sized coal particle size spectra, and a complete sink-float washability analysis.

To arrive at a design basis for each cleaning process, continuous mining techniques were assumed, generally meaning an increase in the impurity level of the ROM coal and a lowering of the particle size spectrum. Coal size consists were extrapolated from similar coals originating in the same geological areas, and it was necessary to extrapolate the washability data obtained from ref. 1 to finer-sized coals and also to interpolate the data for intermediate float-sink specific gravities.

3.4.1.1 Cleaning plant location. The coal beneficiation facilities were premised to be located at the coal mine mouth and were designed to receive ROM coal by conveyor. The ROM coal ranges up to 24 in. in size. Because significant amounts of rocks are usually received with the ROM coal, an average of 10% was used in this evaluation for the various coal feeds. The rock was premised to be rejected in the primary reduction operation and subsequently joins the cleaning plant refuse stream for eventual disposal at the mine.

3.4.1.2 Coal mine capacities. One important aspect that should be noted is that the output from current mines ranges up to about 4 to 5 million tons of coal per year, although 2 to 4 million tons per year is a more realistic value. Hence, a prerequisite for the 15,000-ton/day (maf) product cleaning facility would be a mine production capability of 7 to 9 million tons/year of ROM coal or, alternatively, an ROM coal supply from more than one mine. In the case where coal would be obtained from more than one source, a transportation cost would be incurred for a portion of the coal. However, for this study a single ROM coal source was assumed.

3.4.1.3 Coal storage. A 20-day live coal surface storage supply was planned for the beneficiation plant. No dead storage facilities were designed for the plants. The storage yard will provide a small degree of blending of the raw coal. Conical piles were planned for the 1500-ton/day plants, and parallel piles were planned for the 15,000-ton/day facilities. In all cases, the coal was assumed to be sized prior to the coal yard.

3.4.1.4 Beneficiation plant operating schedule. The 1500-ton/day conceptual plants were designed to operate 8 hr/day, 5 days/week for about 329 days/year, whereas the 15,000-ton/day plants were designed to operate 16 hr/day, 7 days/week for about 329 days/year.

3.4.1.5 Freshwater supply. No treatment of freshwater supply to the cleaning plants was assumed to be required unless (occasionally) the sediment concentration became high or if an acid condition existed.

Because grassroots facilities were planned and relatively small freshwater requirements were anticipated, the water-treatment equipment required for boiler feed and potable water supplies is expected to handle these infrequent occurrences.

3.4.1.6 Water handling. Closed process water loops were used to eliminate stream pollution. The process wash water is treated in thickeners and, with the aid of flocculants, the wash water solid concentrations are controlled. Both the overflow and the underflow from the system are filtered. The filtrate is recycled to the plant, while the filter cake is discarded as refuse. The plant water losses are limited to water associated with the coal product, refuse, and the coal drying operation.

3.4.1.7 Air quality control. No significant air pollution is expected from the wet mechanical beneficiation facilities with the exception of those plants that require coal drying sections. The dryer exhausts were fitted with wet scrubbers to ensure that particulate emissions complied with existing regulations. However, the dryers for the 15,000-ton/day plants are fired with cleaned product coal, and the resulting flue gas in most instances may not meet EPA sulfur oxide emissions standards. The steam-electric power generation unit also uses the same cleaned product as fuel and also may have sulfur oxide emissions above legally permissible standards. To regulate the sulfur oxide emissions, the flue gas streams are combined and treated in limestone slurry flue gas desulfurization units. The boiler ash, excess lime, and fixed, dewatered calcium sulfate are combined and disposed off with other plant refuse.

3.4.1.8 Solid wastes. The principal sources of solid waste materials from wet mechanical beneficiation plants are reject rock from the rotary breakers, high-ash, high-sulfur refuse from the jig or secondary heavy-medium cyclones, and filter cake waste containing primarily clay and slimes separated from the coal fines. Steam plant ash and flue gas scrubber solids are expected to be only about 10% of the cleaning plant waste. The solid wastes are assumed to be disposed of at the mine site.

3.4.2 Mild-cleaning wet beneficiation process description

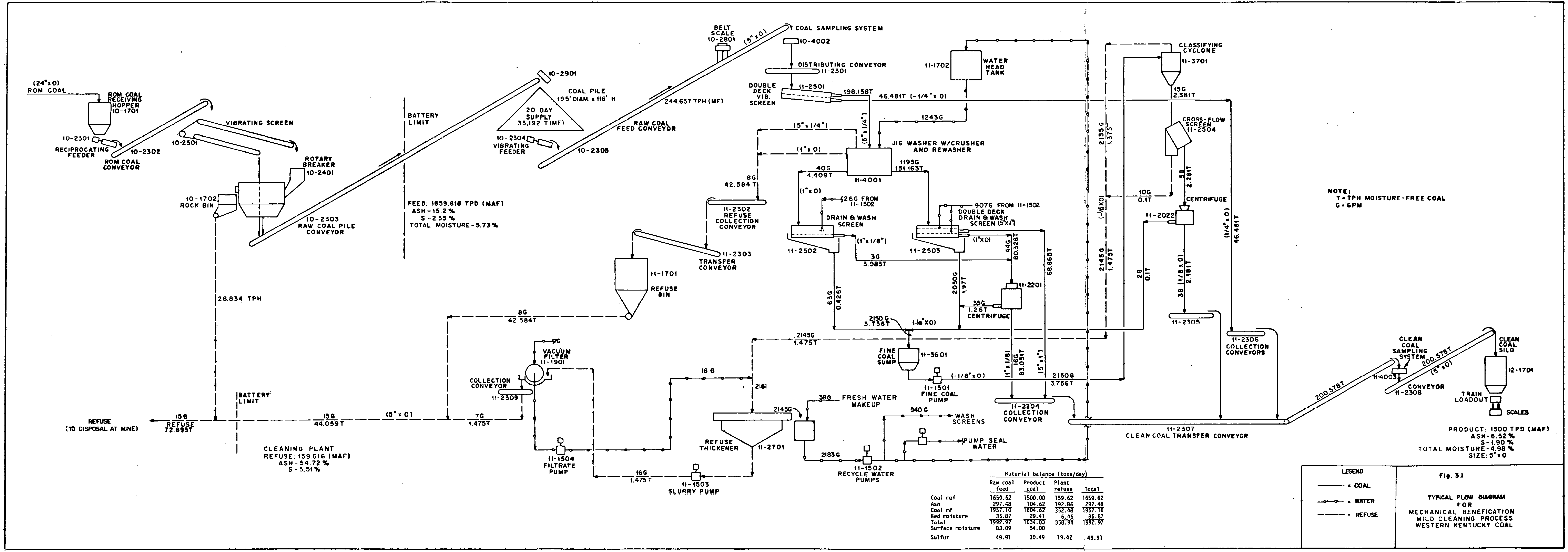
The mild-cleaning process (at 1500- and 15,000-ton/day MAF capacities) is designed to lower the ash and sulfur components with a minimum of heating value losses and in the most economical way. Process flow diagrams, Figs. 3.1 and 3.2, show the mild-cleaning systems at the 1500- and 15,000-ton/day levels respectively. Western Kentucky coal was used in the 1500-ton/day flowsheet and Pennsylvania coal in the 15,000-ton/day flowsheet. The chemical analyses of the raw coals are summarized in Table 1.2. The bed moisture for the coals is also shown in that table. A surface moisture content of 4% was used, in addition to the bed moisture, in the design of the cleaning plants. The equipment lists for these two plants are reported in Appendix C.

The ROM coal is reduced to a 5 in. x 0 size in rotary breakers and is transferred to the coal storage area. This section of the process is designed to operate 8 hr/day, 5 days/week.

Raw coal is conveyed into the cleaning plant and screened into coarse (5 x 1/4 in.) and fine (-1/4 in. x 0) coal fractions. The fine coal fraction bypasses cleaning operations and, by not wetting the fine coal, it is possible to eliminate coal drying operations from the mild treatment facility and yet meet the 5% nominal moisture content for the total plant capacity. This is accomplished by blending the cleaned wet coarse fractions containing less than 5% moisture with the fine coal.

The coarse coal (5 x 1/4 in.) is beneficiated in a three-product jig washer fitted with a middlings crusher and rewasher. The three products from the jig washer are the cleaned coal fraction, the middlings fraction, and the refuse fraction, all 5 x 1/4 in. in size. The middlings fraction, still containing a high percentage of impurities, is resized to 1 in. x 0 to liberate additional impurities and is then rewashed. The recleaned middlings material is dewatered and rinsed on screens. The main (5 x 1/4 in.) cleaned coal fraction is screened into 5 x 1 in. and 1 x 1/4 in. sizes. The 1 x 1/4 in. material is combined with the recleaned middlings and further dewatered in a basket centrifuge.

ORNL DWG 77-623

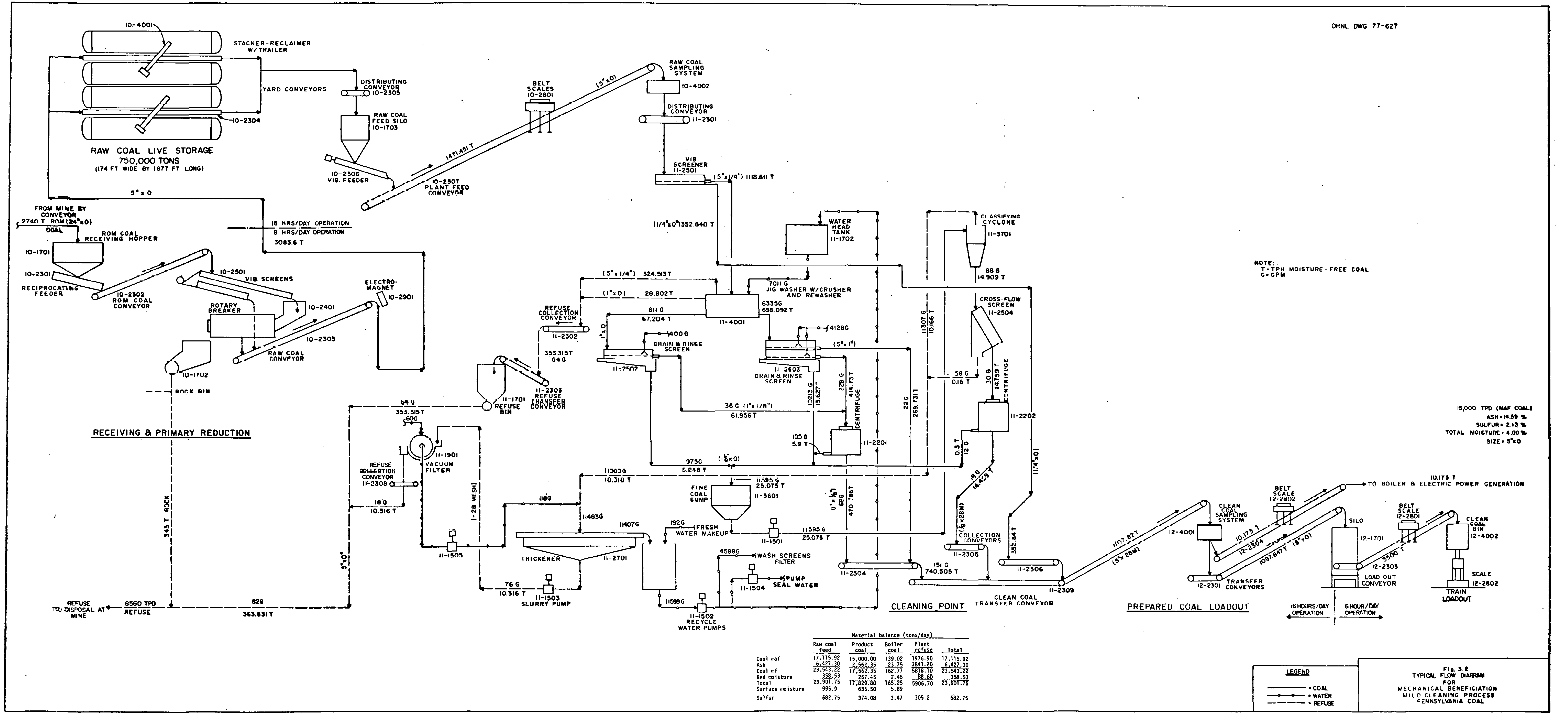


Material balance (tons/day)

	Raw coal feed	Product coal	Plant refuse	Total
Coal maf	1659.62	1500.00	159.62	1659.62
Ash	297.48	104.62	192.86	297.48
Coal mf	1957.10	1604.62	352.48	1957.10
Bed moisture	35.87	29.41	6.46	35.87
Total	1992.97	1634.03	358.94	1992.97
Surface moisture	83.09	54.00		
Sulfur	49.91	30.49	19.42	49.91

Fig. 3.1

TYPICAL FLOW DIAGRAM
FOR
MECHANICAL BENEFICATION
MILD CLEANING PROCESS
WESTERN KENTUCKY COAL



Material balance (tons/day)

	Raw coal feed	Product coal	Boiler coal	Plant refuse	Total
Coal maf	17,115.92	15,000.00	139.02	1976.90	17,115.92
Ash	6,427.30	2,562.35	23.75	3841.20	6,427.30
Coal mf	23,543.22	17,562.35	162.77	5818.10	23,543.22
Bed moisture	358.53	267.45	2.48	88.60	358.53
Total	23,901.75	17,829.80	165.25	5906.70	23,901.75
Surface moisture	995.9	635.50	5.89		
Sulfur	682.75	374.08	3.47	305.2	682.75

Fig. 3.2
TYPICAL FLOW DIAGRAM
FOR
MECHANICAL BENEFICIATION
MILD CLEANING PROCESS
PENNSYLVANIA COAL

The underflows from screening operations and the dewatering centrifuge (containing fine coal) are collected in a sump and pumped to a classifying and dewatering cyclone. The cyclone underflow containing the high-ash material reports to a thickener. The thickener underflow is filtered, and the filter cake is conveyed to the refuse stream. The clarified water overflow from the thickener is recycled. The cleaned coal fraction is then blended with the fine coal fraction, which bypasses the cleaning circuit and is conveyed to a storage silo (1500- or 15,000-ton capacity).

A secondary ground storage area was planned for clean coal storage when major equipment failures occur in the clean coal storage or coal loadout systems or in the event that empty coal cars are not available. Mobile equipment will be used to retrieve coal from the ground storage area.

The smaller-capacity (1500-ton/day) mild-cleaning plant is operated with one production line 8 hr/day, 5 days/week. In the larger-capacity (15,000-ton/day) plant, operation is 16 hr/day, 7 days/week, and two parallel lines are needed. All loadout facilities are operated one shift per day.

3.4.3 Deep-cleaning wet beneficiation process description

The flow diagrams for the proposed deep-cleaning wet beneficiation plants are shown in Figs. 3.3 and 3.4 for the 1500- and 15,000-ton/day capacity plants. Western Kentucky coal is used in each of the flow diagrams to typify the coal flows. The design of both plants is the same except that one process line is used in the smaller-capacity process, and the plant cleaning section is operated 8 hr/day, 5 days/week. In the 15,000-ton/day capacity process, two parallel lines are required and operate 16 hr/day, 7 days/week. The receiving, primary reduction, and coal loadout units of both capacity plants operate 8 hr/day.

The ROM coal is reduced to a 1-1/2 in. x 0 size in rotary breakers to free more of the impurities than accomplished in the mild-cleaning processes in which the ROM coal was reduced to only 5 in. x 0. The sized raw coal (1-1/2 in. x 0) is wet screened into 1-1/2 in. x 28 mesh and -28 mesh x 0 fractions. The coarse coal (1-1/2 in. x 28 mesh) cleaning

	Material balance (tons/day)			
	Raw coal feed	Product coal[a]	Plant refuse	Total
Coal maf	1675.64	1500.00	175.64	1675.64
Ash	300.35	60.71	239.64	300.35
Coal mf	1975.99	1560.71	415.28	1975.99
Bed moisture	36.22	28.61	7.61	36.22
Total	2012.21	1589.32	422.89	2012.21
Surface moisture	83.89	53.53		
Sulfur	50.39	28.72	21.67	50.39

[a] Product coal dried to total moisture content of 5%.

FIG. 3.3

TYPICAL FLOW DIAGRAM
FOR
MECHANICAL BENEFICATION
DEEP CLEANING
PROCESS
WESTERN KENTUCKY COAL

Material balance (tons/day)

	Raw coal feed	Product coal[a]	Boiler coal[a]	Dryer coal	Plant refuse	Total
Coal maf	17,021.3	15,000.0	220.9	16.3	1784.1	17,021.3
Ash	3,051.0	607.1	8.9	0.7	2434.3	3,051.0
Coal mf	20,072.3	15,607.1	229.8	17.0	4218.4	20,072.3
Bed moisture	367.9	286.1	4.2	0.3	77.3	367.9
Total	20,440.2	15,893.2	234.0	17.3	4295.7	20,440.2
Surface moisture	652.2	535.3	7.9	0.6		
Sulfur	511.8	287.2	4.2	0.3	220.1	511.9

[a] Product and boiler coal dried to a total moisture content of 5%.

Fig. 3.4

TYPICAL FLOW DIAGRAM
FOR
MECHANICAL BENEFICIATION
DEEP CLEANING PROCESS
WESTERN KENTUCKY COAL

PAGES 48 to 50

WERE INTENTIONALLY

LEFT BLANK

process is a two-stage heavy-medium cyclone separation system in which magnetite is used as the heavy medium. In stage one, the coal and heavy-medium slurry (sp gr 1.38 for western Kentucky coal) feed by gravity to the separating cyclone at a feed pressure of 15 to 18 psig. The cleaned coal overflows the cyclone and passes consecutively over stationary cross-flow screens and vibrating rinse-and-drain screens, through a dewatering centrifuge, and is discharged to the clean coal collection conveyor.

The underflow from stage one flows over stationary cross-flow screens and then vibrating screens to separate the material into 1-1/2 x 3/8 in. and 3/8 in. x 28 mesh fractions. To liberate more of the impurities, the 1-1/2 x 3/8 in. material is reduced to 3/8 in. x 0 and the 28 mesh x 0 portion removed by vibrating screens. All of the 3/8 in. x 28 mesh material is combined, and the combined stream flows to the second-stage feed sump. The slurry is adjusted to a specific gravity of 1.85 and is then pumped to the second-stage heavy-medium cyclone. Again as in stage 1, cleaned coal overflows the cyclone onto cross-flow screens, rinse and drain screens, through a dewatering centrifuge, and onto the clean coal collection conveyor. The second-stage underflow containing high-ash, high-sulfur material flows over cross-flow screens, drain and rinse screens, and onto a collection conveyor and then to eventual disposal.

The function of the cross-flow screens is to separate most of the heavy medium from the coal or waste material. The heavy medium returns to the respective heavy-medium sump for reuse. The underflow from the drain and rinse screens, which contains diluted medium and some -28 mesh coal resulting mostly from attrition, is piped to a dilute-medium clarifier. The clarified water overflow is recycled, and the underflow is pumped to magnetic drum separators. The magnetite and fine coal are separated, and each is recycled in the process.

The fine coal (-28 mesh x 0) separated at the beginning of the process is collected in a fine coal sump along with the other fine coal streams created by the two-stage heavy-medium circuits. This slurry is pumped to classifying water cyclones, and a separation of the ±100 mesh material is made. The overflow from the cyclones containing very fine coal, slimes, and clays is conveyed to froth flotation cells for final cleaning. The overflow concentrate, which consists of clean coal from the flotation units, is combined with the cyclone classifier underflow clean coal (28 x 100 mesh). The cleaned coal from the latter two operations is very fine (-28 mesh x 0) and retains about 24% surface moisture. Therefore, to achieve an overall product-coal moisture content of no more than 5%, part of the fine coal must be dried before it is finally blended with the outgoing coal stream. The high-ash underflow from the flotation cells is piped to thickeners where the solids are separated with the aid of a flocculating agent. Clear water overflow is recycled, and the thickened underflow containing waste material is filtered. This portion of the waste is combined with the waste stream from the second-stage separation and the reject rock from the primary size-reduction step. The combined waste stream is then trucked to the mine disposal area.

3.4.4 Economic analyses procedure for the wet mechanical beneficiation processes

Economic evaluations were performed using the discounted cash flow (DCF) rate-of-return method for the following cases of the wet mechanical beneficiation processes evaluated:

1. plant sizes — 1500 and 15,000 tons/day of maf product coal;
2. plant types — grassroots and battery-limits; and
3. coal cleaning levels — mild and deep cleaning.

Capital costs for the mechanical beneficiation facilities were obtained from several sources:

1. estimates of individual equipment items taken from the literature and corrected for escalation by cost indexes to January 1977;
2. scaling of vendor estimates for similar type beneficiation facilities[20] (a scaling factor of the 0.7 power of the plant capacities was employed for the larger plants); and
3. application of the coal preparation factoring model[21] for estimating capital and operating costs for coal preparation facilities.

The cost estimates developed are factored estimates with a probable accuracy of ±30%.

Further details regarding the basis for the economic evaluations are given in Appendix A. The results of the analyses are summarized in the following section.

3.4.5 Results and discussion of results

The results of the preliminary process design and economic analyses are summarized separately below for the grassroots and the battery-limits type facilities.

3.4.5.1 Results for the grassroots facilities. Table 3.2 summarizes the results for conceptual plants beneficiating Pennsylvania, western Kentucky, and Illinois coals at a nominal daily production rate of 1500 tons of maf coal. Table 3.3 presents similar results for the 15,000-ton/day plants. Of the three coals examined, the Pennsylvania coal responded best to the washing methods. The percentage recovery of the heating value for the Pennsylvania coal was essentially the same as for the other two coals, but the amount of ash removal by beneficiation was significantly greater.

For the mild-cleaning process, beneficiation costs for Pennsylvania coal were calculated to be \$6.03 and \$3.93 per ton of mf (moisture-free) feed coal for the 1500- and 15,000-ton/day capacity levels, respectively, whereas for the deep-cleaning method the costs increased to \$8.06 and \$5.43 per ton at the same production capacities. The beneficiation costs reported in Tables 3.2 and 3.3 are the costs involved in beneficiating the coal; they do not include the cost of the ROM coal used to produce the cleaned product coal. The ROM coal cost is added to the beneficiation cost to yield the calculated (and reported) cleaned product coal price. The beneficiation costs shown in Tables 3.2 and 3.3 were calculated for an ROM coal cost of \$20 per ton, annual after-tax rate of return on equity of 12%, a debt/equity ratio of 70:30, and an annual interest rate of 9% on the debt.

A summary of the various capital and operating costs and the product coal price (for 12 and 15% rate of return on equity capital) is reported in Table 3.4 for Pennsylvania, western Kentucky, and Illinois coals. The estimated direct capital cost for like cleaning methods is the same for

Table 3.2. Wet mechanical beneficiation summary for grassroots facility (capacity — 1500 tons/day of maf product coal)

	Pennsylvania coal				Western Kentucky coal				Illinois coal			
	Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	2377	1728	2344	1704	1997	1694	2044	1734	1985	1622	2099	1716
Ash, %	27.3		27.3		15.2		15.2		18.25		18.25	
Sulfur, %	2.90		2.90		2.55		2.55		4.21		4.21	
Total moisture, %	5.44		5.44		5.73		5.73		5.9		5.9	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
B. Clean product coal	1756	1500	1620	1500	1605	1500	1561	1500	1694	1500	1625	1500
Ash, %	14.59		7.42		6.52		3.89		11.45		7.68	
Sulfur, %	2.13		1.64		1.90		1.84		3.13		2.80	
Total moisture, %	4.89		5.0		4.98		5.0		4.87		5.0	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		52.51		51.79		48.67		49.82		45.03		47.63
Clean product coal		45.58		45.58		43.10		43.10		41.63		41.63
Percent recovery												
Material[a]	73.9		69.1		80.3		76.3		85.4		77.4	
Thermal[b]		86.8		88.0		88.6		86.5		92.5		87.4
Beneficiation cost[c,d]												
$ per ton	6.03		8.06		6.25		8.36		5.84		7.64	
¢ per million Btu		24		30		25		30		25		31

[a] $\text{Material recovery} = \left(\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}}\right) \times 100.$

[b] $\text{Thermal recovery} = \left(\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}}\right) \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 3.3. Wet mechanical beneficiation summary for grassroots facility (capacity — 15,000 tons/day of maf product coal)

	Pennsylvania coal				Western Kentucky coal				Illinois coal			
	Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	23,543	17,116	23,005	16,725	19,746	16,745	20,072	17,021	19,540	15,974	20,545	16,795
Ash, %	27.3		27.3		15.2		15.2		18.25		18.25	
Sulfur, %	2.90		2.90		2.55		2.55		4.21		4.21	
Total moisture, %	5.44		5.44		5.73		5.73		5.9		5.9	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
B. Clean product coal	17,562	15,000	16,202	15,000	16,046	15,000	15,607	15,000	16,940	15,000	16,248	15,000
Ash, %	14.59		7.42		6.52		3.89		11.45		7.68	
Sulfur, %	2.13		1.64		1.90		1.84		3.13		2.80	
Total moisture, %	4.89		5.0		4.98		5.0		4.87		5.0	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		520.1		508.2		481.1		489.1		443.3		466.1
Clean product coal		455.8		455.8		431.0		431.0		416.3		416.3
Percent recovery												
Material[a]	74.6		70.4		81.3		77.8		86.7		79.1	
Thermal[b]		87.6		89.7		89.6		88.1		93.9		89.3
Beneficiation cost[c,d]												
$ per ton	3.93		5.43		3.92		4.99		3.65		5.09	
¢ per million Btu		16		20		15		19		16		21

---

[a] Material recovery = $\left(\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}}\right) \times 100.$

[b] Thermal recovery = $\left(\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}}\right) \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 3.4. Summary of the capital and operating costs, and the calculated product coal price for the wet beneficiation processes[a]

Facility type: grassroots

Coal type	Cleaning level	Direct capital cost ($10^6)	Annual operating cost ($10^6)	Working capital cost ($10^6)	Total capital investment ($10^6)	Product coal price[b] ($/ton) for annual after-tax rate of return on equity of: 12%	15%
PLANT CAPACITY — 1500 tons/day of maf PRODUCT COAL[c]							
Pennsylvania	Mild	6.25	1.91	2.69	11.09	33.15	33.45
	Deep	8.31	2.31	2.59	13.75	37.00	37.39
Western Kentucky	Mild	6.25	1.75	2.39	10.79	31.16	31.47
	Deep	8.31	2.33	2.42	13.59	34.56	34.95
Illinois	Mild	6.25	1.69	2.46	10.85	29.27	29.57
	Deep	8.31	2.12	2.48	13.65	33.48	33.87
PLANT CAPACITY — 15,000 tons/day of maf PRODUCT COAL[d]							
Pennsylvania	Mild	39.08	11.14	26.19	78.37	30.75	30.98
	Deep	55.05	14.23	25.02	98.29	33.83	34.14
Western Kentucky	Mild	39.08	9.54	23.16	75.34	28.54	28.77
	Deep	55.05	11.20	23.03	96.30	30.71	31.02
Illinois	Mild	39.08	9.02	23.83	76.01	26.71	26.93
	Deep	55.05	12.65	23.93	97.20	30.38	30.68

[a] For 90% plant service factor.

[b] Calculated product coal price is based on $20 per ton ROM coal, 70:30 debt/equity ratio, and 9% annual interest rate on the debt fraction of capital. This price includes the ROM coal cost.

[c] Plant operates 1 shift/day, ~5 days/week with 90% annual plant service factor.

[d] Plant operates 2 shifts/day, ~7 days/week with 90% annual plant service factor.

all coals at like production levels because the variation in the raw coal throughput is relatively minor. Total capital investment costs (for the Pennsylvania coal, for example) for the 1500- and 15,000-ton/day mild-cleaning methods are $11.09 and $78.37 million respectively. In comparison, the total capital investment costs for the deep-cleaning processes are $13.76 and $98.29 million for the different plant capacity levels. Similar investment costs for the western Kentucky and Illinois coals are given in Table 3.4.

Small variations are indicated in the working capital, annual operating cost, and total capital investment estimates for the three coals under comparative conditions. The product coal prices reported in Table 3.4 are based on $20 per ton ROM coal, 70:30 debt/equity ratio, and 12 and 15% annual rate of return on equity. For corresponding cleaning procedures, the higher-capacity coal washing facilities produce clean coal at somewhat lower costs — about 8% lower for the mild method and about 10% less for the deep-cleaning process.

Results of the economic analyses of the wet beneficiation processes for the three coals are presented in graphical form in Appendix B. The graphs indicate the variations of the cleaned coal product price for various ROM coal costs ranging between $10 per ton and $50 per ton, debt/equity ratios of 0:100, 30:70, 70:30, and 95:5, and for 12 and 15% annual after-tax rate of return on equity.

Detailed breakdowns of the various cost items that constitute the annual operating cost, working capital, and total capital investment are presented in Tables 3.5, 3.6, and 3.7 respectively. The data are presented for both the mild- and the deep-cleaning processes and for the 1500- and 15,000-ton/day product coal plant sizes.

3.4.5.2 Results for the battery-limits facilities. Analyses similar to those described above for the grassroots facilities were performed for the battery-limits facilities except that all the plant utility requirements were purchased. The results of these analyses are presented in Tables 3.8-3.13 and in graphical form in Appendix B.

3.4.5.3 Discussion regarding the ash and sulfur reduction achieved. Because mechanical beneficiation processes are inherently limited to the lowering of the ash and pyritic sulfur (thereby also the total sulfur)

Table 3.5. Annual operating cost summary for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: grassroots

All values are in millions of dollars.

Cost component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Utilities[a]												
Electric power (generated onsite)	0 0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chemicals[a] (includes process water)	0.005	0.185	0.005	0.122	0.005	0.136	0.134	0.943	0.105	0.745	0.156	0.883
Operating labor costs												
Process operating labor	0.310	0.310	0.310	0.310	0.310	0.310	0 833	0.874	0.833	0.874	0.833	0.874
Supervisory personnel cost	0.062	0.062	0.062	0.062	0.062	0.062	0 167	0.175	0.167	0.175	0.167	0.175
Labor burden	0.130	0.130	0.130	0.130	0.130	0.130	0.350	0.367	0.350	0.367	0.350	0.367
Plant maintenance cost (includes maintenance materials, labor, labor supervision, and labor burden)	0.406	0.540	0.406	0.540	0.406	0.540	2.540	3.579	2.540	3.579	2.540	3.579
Operating supplies[a]	0.093	0.093	0.093	0.093	0.093	0.093	0.250	0.262	0.250	0.262	0.250	0.262
General administrative overhead costs	0.324	0.377	0 324	0.377	0.324	0.377	1.449	1.886	1.449	1.886	1.449	1.886
Waste disposal cost[a]	0.587	0.614	0.407	0.696	0.341	0.452	5.615	6.338	3.869	3.164	3.238	4.638
Property insurance cost	0.064	0.085	0.064	0.085	0.064	0.085	0.399	0 562	0.399	0.562	0.399	0.562
Total gross operating cost[b]	1.981	2.396	1.801	2.415	1.735	2.185	11.737	14 986	9.962	11.614	9.382	13.226
By-product credit[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total net operating cost[b]	1.981	2.396	1.801	2.415	1.735	2.185	11.737	14.986	9.962	11.614	9.382	13.226

---

[a] The costs shown are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an "a" by the desired plant service factor to obtain the appropriate annual operating cost.

[b] The costs shown do not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately in the computer program PRP. See Appendix A for further details.

Table 3.6. Working capital estimate for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: grassroots

All values are in millions of dollars.

Coal component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Raw coal inventory at $20 per ton (20 days)	0.951	0.938	0.799	0.818	0.794	0.840	9.417	9.202	7.898	8.029	7.816	8.218
Product coal inventory at $30 per ton (30 days)	1.580	1.458	1.445	1.405	1.525	1.462	15.806	14.582	14.442	14.046	15.246	14.623
Gross operating cost (30 days)	0.163	0.197	0.148	0.199	0.143	0.180	0.965	1.232	0.819	0.954	0.771	1.087
Total working capital	2.694	2.593	2.392	2.422	2.462	2.482	26.188	25.016	23.159	23.029	23.833	23.928

Table 3.7. Capital investment summary for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: grassroots

All values are in millions of dollars.

Cost component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Total direct plant cost, D	6.25	8.31	6.25	8.31	6.25	8.31	39.08	55.05	39.08	55.05	39.08	55.05
Engineering and contractor's fee, 15% D	0.94	1.25	0.94	1.25	0.94	1.25	5.86	8.26	5.86	8.26	5.86	8.26
Project contingency, 15% D	0.94	1.25	0.94	1.25	0.94	1.25	5.86	8.26	5.86	8.26	5.86	8.26
Start-up plant modifications, 2% D	0.12	0.16	0.12	0.16	0.12	0.16	0.78	1.10	0.78	1.10	0.78	1.10
Working capital	2.69	2.59	2.39	2.42	2.46	2.48	26.19	25.02	23.16	23.03	23.83	23.93
Land cost	0.15	0.20	0.15	0.20	0.15	0.20	0.60	0.60	0.60	0.60	0.60	0.60
Total capital investment	11.09	13.76	10.79	13.59	10.86	13.65	78.37	98.29	75.34	96.30	76.01	97.20

Table 3.8. Wet mechanical beneficiation summary
Plant capacity: 1500 tons/day of maf product coal
Facility type: battery limits

	Pennsylvania coal				Western Kentucky coal				Illinois coal			
	Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	2345	1705	2239	1664	1963	1665	1986	1685	1949	1622	2039	1667
Ash, %	27.3		27.3		15.2		15.2		18.25		18.25	
Total sulfur, %	2.90		2.90		2.55		2.55		4.21		4.21	
Total moisture, %	5.44		5.44		5.73		5.73		5.9		5.9	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
B. Clean coal product	1756	1500	1520	1500	1605	1500	1561	1500	1694	1500	1625	1500
Ash, %	14.59		7.42		6.52		3.89		11.45		7.68	
Total sulfur, %	2.13		1.54		1.90		1.84		3.13		2.80	
Total moisture, %	4.89		5.0		4.98		5.0		4.87		5.0	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		51.30		50.58		47.84		48.40		44.23		46.27
Clean coal product		45.58		45.58		43.10		43.10		41.63		41.63
Percent recovery												
Material[a]	74.9		70.8		81.7		78.6		86.9		79.7	
Thermal[b]		88.0		90.1		90.1		89.1		94.1		90.0
Beneficiation cost[c,d]												
\$ per ton	5.06		6.37		5.18		6.98		4.81		6.31	
¢ per million Btu		21		26		20		27		21		26

---

[a] $$\text{Material recovery} = \left(\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}}\right) \times 100.$$

[b] $$\text{Thermal recovery} = \left(\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}}\right) \times 100.$$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on \$20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 3.9. Wet mechanical beneficiation summary

Plant capacity: 15,000 tons/day of maf product coal

Facility type: battery limits

	Pennsylvania coal				Western Kentucky coal				Illinois coal			
	Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning		Mild cleaning		Deep cleaning	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	23,327	16,959	22,746	16,536	19,602	16,623	19,781	16,775	19,353	15,821	20,291	16,588
Ash, %	27.3		27.3		15.2		15.2		18.25		18.25	
Total sulfur, %	2.90		2.90		2.55		2.55		4.21		4.21	
Total moisture, %	5.44		5.44		5.73		5.73		5.9		5.9	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
B. Clean coal product	17,562	15,000	16,202	15,000	16,046	15,000	15,607	15,000	16,940	15,000	16,248	15,000
Ash, %	14.59		7.42		6.52		3.89		11.45		7.68	
Total sulfur, %	2.13		1.64		1.90		1.84		3.13		2.80	
Total moisture, %	4.89		5.0		4.98		5.0		4.87		5.0	
HHV, Btu/lb		15,194		15,194		14,367		14,367		13,877		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		515.3		502.5		477.6		482.0		439.1		460.4
Clean coal product		455.8		455.8		431.0		431.0		416.3		416.3
Percent recovery												
Material[a]	75.3		71.2		81.9		78.9		87.5		80.1	
Thermal[b]		88.5		90.7		90.3		89.4		94.8		90.4
Beneficiation cost[c,d]												
$ per ton	3.97		5.56		3.97		5.12		3.66		5.22	
¢ per million Btu		16		21		16		20		14		21

[a] Material recovery = $\left(\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}}\right) \times 100.$

[b] Thermal recovery = $\left(\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}}\right) \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 3.10. Summary of the capital and operating costs, and the calculated product coal price for the wet beneficiation processes[a]

Facility type: battery limits

Coal type	Cleaning level	Direct capital cost ($10^6)	Annual operating cost ($10^6)	Working capital cost ($10^6)	Total capital investment ($10^6)	Product coal price[b] ($/ton) for annual after-tax rate of return on equity of: 12%	15%
		PLANT CAPACITY — 1500 tons/day of maf PRODUCT COAL[c]					
Pennsylvania	Mild	5.51	1.48	2.65	10.08	31.76	32.03
	Deep	6.78	1.98	2.55	11.71	35.13	35.46
Western Kentucky	Mild	5.51	1.33	2.34	9.77	29.64	29.93
	Deep	6.78	1.98	2.37	11.53	32.43	32.77
Illinois	Mild	5.51	1.27	2.41	9.84	27.83	28.10
	Deep	6.78	1.76	2.43	11.59	31.41	31.74
		PLANT CAPACITY — 15,000 tons/day of maf PRODUCT COAL[d]					
Pennsylvania	Mild	36.58	11.80	26.18	75.07	30.53	30.75
	Deep	51.54	15.60	24.95	93.58	33.64	33.93
Western Kentucky	Mild	36.58	10.23	23.18	72.07	28.40	28.62
	Deep	51.54	12.74	23.06	91.69	30.47	30.77
Illinois	Mild	36.58	9.66	23.83	72.72	26.51	26.73
	Deep	51.54	14.07	23.97	92.60	30.20	30.48

[a] For 90% plant service factor.

[b] Calculated product coal price is based on $20 per ton ROM coal, 70:30 debt/equity ratio, and 9% annual interest rate on the debt fraction of capital. This price includes the ROM coal cost.

[c] Plant operates 1 shift/day, ~5 days/week with 90% annual plant service factor.

[d] Plant operates 2 shifts/day, ~7 days/week with 90% annual plant service factor.

Table 3.11. Annual operating cost summary for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: battery limits

All values are in millions of dollars.

Cost component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Utilities[a]												
Electric power at 2.5¢/kWhr	0.261	0.548	0.261	0.548	0.261	0.548	3.001	3.921	3.001	3.921	3.001	3.921
Chemicals[a] (includes process water)	0.005	0.185	0.005	0.122	0.005	0.136	0.129	1.094	0.129	0.896	0.129	1.028
Operating labor costs												
Process operating labor	0.117	0.117	0.117	0.117	0.117	0.117	0.413	0.517	0.413	0.517	0.413	0.517
Supervisory personnel cost	0.024	0.024	0.024	0.024	0.024	0.024	0.083	0.103	0.083	0.103	0.083	0.103
Labor burden	0.049	0.049	0.049	0.049	0.049	0.049	0.173	0.217	0.173	0.217	0.173	0.217
Plant maintenance cost (includes maintenance materials, labor, labor supervision, and labor burden)	0.275	0.339	0.275	0.339	0.275	0.339	1.829	2.577	1.829	2.577	1.825	2.577
Operating supplies[a]	0.035	0.035	0.035	0.035	0.035	0.035	0.124	0.155	0.124	0.155	0.124	0.155
General administrative overhead costs	0.171	0.197	0.171	0.197	0.171	0.197	0.946	1.299	0.946	1.299	0.946	1.299
Waste disposal cost[a]	0.572	0.544	0.407	0.546	0.346	0.298	5.615	6.338	3.869	3.164	3.238	4.635
Property insurance cost	0.056	0.069	0.056	0.069	0.056	0.069	0.373	0.527	0.373	0.527	0.373	0.527
Total gross operating cost[b]	1.565	2.107	1.400	2.046	1.339	1.812	12.686	16.748	10.940	13.376	10.309	14.979
By-product credit[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total net operating cost[b]	1.565	2.107	1.400	2.046	1.339	1.812	12.686	16.748	10.940	13.376	10.309	14.979

[a] The costs shown are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an "a" by the desired plant service factor to obtain the appropriate annual operating cost.

[b] The costs shown do not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately in the computer program PRP. See Appendix A for further details.

Table 3.12. Working capital estimate for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: battery limits

All values are in millions of dollars.

Cost component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Raw coal inventory at $20 per ton (20 days)	0.938	0.916	0.785	0.795	0.780	0.816	9.331	9.098	7.841	7.913	7.741	8.116
Product coal inventory at $30 per ton (30 days)	1.581	1.458	1.444	1.405	1.524	1.462	15.806	14.582	14.442	14.046	15.246	14.623
Gross operating cost (30 days)	0.129	0.173	0.115	0.168	0.110	0.149	1.043	1.270	0.899	1.100	0.847	1.231
Total working capital	2.648	2.547	2.344	2.368	2.414	2.427	26.180	24.950	23.182	23.059	23.834	23.970

Table 3.13. Capital investment summary for wet mechanical beneficiation — mild- and deep-cleaning plants

Facility type: battery limits

All values are in millions of dollars.

Cost component	1500-ton/day plant						15,000-ton/day plant					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep	Mild	Deep
Total direct plant cost, D	5.51	6.78	5.51	6.78	5.51	6.78	36.58	51.54	36.58	51.54	36.58	51.54
Engineering and contractor's fee, 15% D	0.83	1.02	0.83	1.02	0.83	1.02	5.49	7.73	5.49	7.73	5.49	7.73
Project contingency, 15% D	0.83	1.02	0.83	1.02	0.83	1.02	5.49	7.73	5.49	7.73	5.49	7.73
Startup plant modifications, 2% D	0.11	0.14	0.11	0.14	0.11	0.14	0.73	1.03	0.73	1.03	0.73	1.03
Working capital	2.65	2.55	2.34	2.37	2.41	2.43	26.18	24.95	23.18	23.06	23.83	23.97
Land cost	0.15	0.20	0.15	0.20	0.15	0.20	0.60	0.60	0.60	0.60	0.60	0.60
Total capital investment	10.08	11.71	9.77	11.53	9.84	11.59	75.07	93.58	72.07	91.69	72.72	92.60

contents of the coal, a comparison of the ash and sulfur reduction achieved by the wet beneficiation processes was studied for the three coals and the two levels of beneficiation evaluated in this study. Table 3.14 presents a summary of the distribution of the ash and sulfur components between the raw coal, cleaned product coal, and the plant refuse streams for the above-mentioned cases. In addition, the reduction achieved in the ash and total sulfur content of the coal due to the beneficiation processes is also presented in Table 3.14.

Referring to Table 3.14, for the mild-cleaning level of beneficiation (in which the fine coal was not wet beneficiated), a moderate ash reduction level was achieved. The ash reduction ranged from about 37% to about 57% for the three coals evaluated. However, for the deep-cleaning level of beneficiation in which the feed coal was of a smaller size and the total throughput of coal was beneficiated, the ash reduction ranged from about 58% to about 74%. This indicates the significant increase in the ash reduction that can be achieved by subjecting the coals to a deeper (fuller) beneficiation process.

The reduction in the sulfur content of the three coals achieved by the wet mechanical beneficiation processes is given in Table 3.15. From Table 3.15, it should be noted that the incremental pyritic sulfur reduction obtained between the deep and the mild beneficiation levels ranges between about 4 and 20%. Information presented in Table 3.15 suggests that no incremental advantage would be gained by the deep beneficiation (over mild beneficiation) of the western Kentucky coal. However, the results for the Pennsylvania coal show a much more significant increase in the sulfur reduction by beneficiating the coal to a deeper level. The Illinois coal examined gave intermediate results.

The significance of the sulfur reduction in the coal by the wet beneficiation processes is further highlighted when the potential SO_2 emission levels from burning the raw and the cleaned product coals are considered. The results of the above comparison are presented in Table 3.16. The SO_2 emission levels shown in Table 3.16 are the emissions that would result if the coals were fired in a conventional utility boiler without any flue-gas scrubbing downstream of the boiler.

Table 3.14. Summary of the ash and total sulfur content of the raw coal, cleaned product, and refuse streams for the conceptual wet mechanical beneficiation plants evaluated

Coal type	Cleaning level	Raw coal feed		Product coal		Refuse		Reduction achieved in the plant product due to beneficiation (%)	
		Ash (%)	Sulfur (%)	Ash (%)	Sulfur (%)	Ash (%)	Sulfur (%)	Ash	Total sulfur
Pennsylvania		27.3	2.9						
	Mild			14.59	2.13	66.0	5.26	46.6	26.6
	Deep			7.42	1.64	77.0	6.05	72.8	43.4
Western Kentucky		15.2	2.55						
	Mild			6.52	1.90	54.7	5.51	57.1	25.5
	Deep			3.89	1.84	57.7	5.22	74.4	27.8
Illinois		18.25	4.21						
	Mild			11.45	3.13	66.0	11.79	37.3	25.7
	Deep			7.63	2.80	61.0	9.92	58.0	33.5

Table 3.15. Sulfur reduction by wet mechanical beneficiation

Coal type	Raw coal feed (% sulfur)		Cleaning level	Product coal (% sulfur)		Sulfur reduction (%)		Incremental sulfur reduction (%) (deep-mild)	
	Total	Pyritic		Total	Pyritic	Total	Pyritic	Total	Pyritic
Pennsylvania	2.90	2.46							
			Mild	2.13	1.69	26.6	31.3	16.8	19.9
			Deep	1.64	1.20	43.4	51.2		
Western Kentucky	2.55	1.69							
			Mild	1.90	1.04	25.5	38.5	2.3	3.5
			Deep	1.84	0.98	27.8	42.0		
Illinois	4.21	2.58							
			Mild	3.13	1.50	25.7	41.9	7.8	12.8
			Deep	2.80	1.17	33.5	54.7		

Table 3.16. Potential reduction in SO_2 stack-gas emission effected by wet mechanical beneficiation — combustion of raw coal vs cleaned coal

Coal type	Cleaning level	Potential SO_2 emission from coal-fired boiler[a] (lb $SO_2/10^6$ Btu) Raw coal	Potential SO_2 emission from coal-fired boiler[a] (lb $SO_2/10^6$ Btu) Product coal	Reduction in SO_2 emission due to coal beneficiation[b] (%)	Incremental SO_2 emission reduction (deep-mild) (%)
Pennsylvania		5.25			
	Mild		3.28	37.5	18.1
	Deep		2.33	55.6	
Western Kentucky		4.19			
	Mild		2.83	32.5	3.8
	Deep		2.67	36.3	
Illinois		7.42			
	Mild		5.09	31.4	9.7
	Deep		4.37	41.1	

[a] Calculated using the equation:

$$\text{Emission, lb } SO_2 \text{ per million Btu} = \frac{20 \times \text{sulfur, percent (maf basis)}}{\text{coal heating value (maf basis), Btu/lb} \times 10^{-3}}$$

[b] Calculated as: $\frac{\text{Raw coal } SO_2 \text{ emission} - \text{product coal SO2 emission}}{\text{raw coal } SO_2 \text{ emission}} \times 100.$

Admittedly, for the three coals evaluated, the potential SO_2 emission levels are much higher than the statutory limits of 1.2 lb SO_2 per million Btu. However, the reduction in the SO_2 emission levels due to beneficiation indicates the potential reduction in the flue-gas scrubbing that would be required downstream of the boiler. The potential SO_2 emission reductions range between about 31 and 56%. It should be noted that the incremental reduction (due to deep over mild beneficiation) in the SO_2 emission levels parallels the incremental sulfur reductions in the coals reported in Table 3.15.

Generally, for the coals evaluated, good recovery of the coal heating values was obtained by both the mild and the deep wet beneficiation processes (see Tables 3.2, 3.3, 3.8, and 3.9), while simultaneously effecting a significant decrease in the mass of the total coal product. This is an important factor when considering transportation costs since more potential heating value (and less refuse) is shipped for transporting the same tonnage of coal than would be the case if the coals were not beneficiated.

Another potential economic benefit that may accrue from beneficiating the coal at (or near) the coal mine is that the refuse generated in the process may be conveniently disposed of at the mine, thereby reducing disposal costs at the end-user facility.

In view of the generally excellent ash reductions achieved (see Table 3.14) and the nearly 50% reduction in the pyritic sulfur content (see Table 3.15) in the coals evaluated when using the deep beneficiation process, the only other measure that could improve the cleaning efficiency would be to further reduce the size of the coal feed processed. Reducing the size of the coal feed would liberate additional impurities that could then be removed. However, it would also increase the processing costs and lower the recovery efficiency.

3.4.6 Material problems associated with wet mechanical beneficiation systems

Although very little data has been published on the subject, the generally accepted design (and operation) of a wet mechanical coal washery is based on one or two shifts per day, 5 or 6 days/week. The offshifts and weekends provide time required for maintenance operations. This is not meant to infer that maintenance is not performed during operational periods but merely to indicate the magnitude of the maintenance problem.

Because coal tonnages are usually high in a wet coal washery, the major maintenance problems relate to erosion, mechanical equipment failure, and some corrosion. Coal, a heterogeneous material made up of components of varying properties, is recognized to be a highly abrasive material. In addition, mineral matter present with the coal adds considerably to the abrasion characteristics of the coal.

In wet mechanical beneficiation plants, the coal is generally transported by conveyors, chutes, or pumps in the form of slurries. In these plants erosion is a primary maintenance problem even though the bins and chutes are provided with abrasion-resistant metal liners, the storage vessels are lined with extra-strong concrete, and slurry-handling pumps are fitted with "Ni-Hard" materials. "Ni-Hard" materials, as the name implies, are a class of materials that are hardened and made abrasion resistant. Other areas of high erosion are the vibrating and stationary screen applications and the size-reduction equipment used in the beneficiation plant.

Mechanical maintenance problems exist throughout a wet mechanical washing plant from the vast amount of conveying, crushing, centrifuging, and filtering equipment present. Equipment susceptible to mechanical failures includes conveyor belts, gear drives, chain drives, and filter mediums.

In summing up the overall status of wet mechanical beneficiation, only small gains can be expected in ash or sulfur removal or processing efficiency due to physical constraints of the separation processes, except possibly in fine coal processing. Cost reductions in the form of lower maintenance costs are anticipated as equipment designs improve.

3.5 Multistream Coal Cleaning System[22]

3.5.1 Process description

The coal beneficiation process, advanced by General Public Utilities (GPU) in association with Heyl and Patterson, Inc., is a wet mechanical beneficiation process and consists essentially of a two-stage heavy-medium cyclone separation facility. A plant based on this process is currently being built at Homer City, Pennsylvania. The system is designed to produce a low-sulfur coal, a medium-sulfur coal, and a refuse stream. The low-sulfur coal will be used in the new boilers, and the medium-sulfur coal will be used in the boilers of existing power generating facilities at Homer City. Utilizing the coals in this way, GPU complies with the current federal and state regulations for SO_x stack gas emissions.

In the multistream coal cleaning process, the ROM coal is crushed to a predetermined size consist and then washed in the first-stage heavy-medium cyclone unit at a relatively high specific gravity. No details of the process separations were provided by GPU, but stage one removes a significant amount of the ash and a large fraction of the pyritic sulfur content of the raw coal, which is discarded as refuse. The overflow or cleaned coal stream from stage one becomes the feed for stage two. The second stage operates at a low specific gravity and merely separates the feed into a high-grade coal (low sulfur, low ash) and a medium-sulfur and -ash product coal. Both stages of the multistream process use magnetite as the heavy medium. Figure 3.5 represents the flow pattern in the multistream cleaning process.

3.5.2 Discussion of multistream cleaning process

The proposed process appears to have drawbacks. First, it was reported that, to be reasonably successful, the organic sulfur content of the raw coal feed should be low, and from the high specific gravity used in stage one it must be assumed that the pyritic sulfur is in a form that is easily beneficiated to lower the sulfur content from 2.7 to 1.7% and recover most of the coal value. A large, well-defined source of coal with the particular beneficiation characteristics must be available; otherwise, a small shift in beneficiation properties could raise the

ORNL DWG 77-654

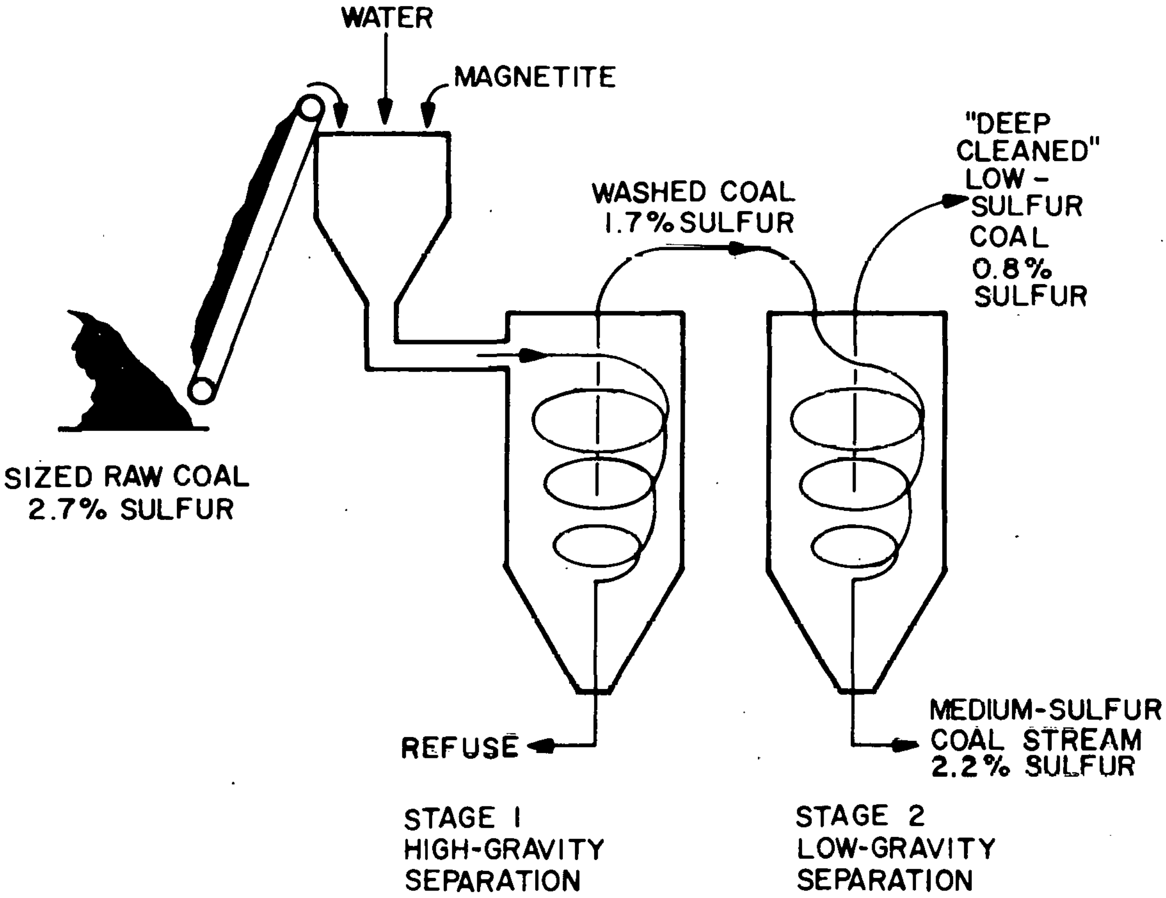


Fig. 3.5. Schematic flow diagram of the multistream cleaning process.

sulfur content of the high-grade coal fraction above the specification level needed for compliance with EPA standards for SO_x emission control for new power generation plants. Furthermore, in the proposed operational sequence, the capital investment and operating costs of stage two approach those of stage one because the capacity of each stage is about equal. The only difference in the capacities of the two stages is that of the refuse stream (about 15 to 18% of the raw coal feed).

If the operational sequence had been reversed with a low-specific-gravity first stage and with the high-grade coal produced from stage one overflow being the feed to the second stage, the design capacity of stage two could have been reduced because the high-grade coal amounts to about 28 to 32% of the raw coal. This would also provide some additional operating flexibility because interstage crushing could be used to liberate more of the impurities, thus lowering the ash and sulfur contents of the medium-sulfur coal and possibly lowering the coal value lost in the waste stream.

3.5.3 Technical and economic evaluation

Existing technology and equipment were used in the design of the multistream coal cleaning system. Very limited facility information was presented, but presumably the facility included a raw coal storage yard, magnetite recycling system, fine coal treatment unit (vibrating tables or froth flotation), water recovery, coal dewatering, coal drying, and dry coal storage as well as the indicated crushing and heavy-medium cyclone separation equipment. The technology discussion presented for the wet mechanical beneficiation deep-cleaning facility also applies to the multistream coal cleaning system.

A capital cost of $35 million was given by GPU for the mine-mouth coal cleaning installation with an indicated annual capacity of 1.3 million tons. Based on estimated capital costs[20] of $72.8 million for a similar facility producing 13.5 million tons/year by McNally Pittsburgh Manufacturing Corporation, the capital cost reported by GPU appears high by a factor of two. Additionally, utilizing a method devised by Fluor Utah, Inc.,[21] for estimating capital costs for wet mechanical beneficiation plants, a ball park figure of about $20 million is calculated for a 1.3 million-ton/year cleaning plant. A comparison of the GPU capital cost with costs calculated for similar mechanical beneficiation systems provided in this document with an annual capacity of about 7 million tons/year indicated a cost of $17 million using a 0.7 power factor on relative plant capacities. However, the battery limits of the GPU coal cleaning plant were not stated, and comparison of the quoted $35 million with the latter two methods of estimating the capital cost may be invalid.

3.6 Otisca Process

3.6.1 Introduction

The Otisca process developed by Otisca Industries, Ltd., is similar to the heavy-medium separation process except that the Otisca process operates under a high vacuum, and the fluid used in this process as the medium is refrigerant R-11 (Freon). The Freon has a specific gravity of 1.5 at 60°F. No water other than that associated with the coal is involved in the process; hence the capital investment and the operating costs are reduced significantly because no dewatering equipment such as screens, vacuum filters, filter presses, etc. is required. The process operates at 1 to 2 in. of water pressure and at about 60 to 68°F. The operating pressure and temperature are determined by the physical properties of the medium (parting liquid).

The developers of the process claim that the process is capable of reducing the ash and the total sulfur content of the coal by about 50 and 44%, respectively, while recovering in excess of 73% of the raw coal as cleaned product coal. In addition, the developers claim that the process can handle any reasonable top size of coal. A 20-ton/hr demonstration-type pilot plant based on the process has been successfully operated by Otisca Industries to beneficiate 5 mesh x 0 size consist Upper Freeport coal from the North Branch mine of the Island Creek Coal Company.

The process consists essentially of mixing the crushed and sized feed coal with the parting liquid (Freon) and allowing the clean coal to be separated from the reject material, which consists chiefly of mineral matter and pyritic sulfur. Because the Freon does not react with the coal matter, the organic sulfur content of the coal is not reduced. A small concentration (generally 0.6 lb per ton of feed coal) of a proprietary additive is added with the parting liquid to help control (1) the middling concentration and (2) the concentration of the water and the included slimes on the coal product. After the heavy-medium type separation, the cleaned coal product is dried to the desired moisture content and shipped as plant product; the reject stream is also dried and disposed of as a plant waste product. The evaporated medium from various sections of the process is collected, compressed, condensed, purified (removal of water and air), and recycled in the process.

According to the process developers,[23] the capital investment for a battery-limits type plant is expected to be around $10,000 per ton per hour of feed coal processed, while the operating costs are estimated to be less than $1 per ton of coal processed. The operating cost reported appears to be very low; however, no independent evaluation has been performed to verify the reported value.

3.6.2 Process description

Figure 3.6 is a block flow diagram of the Otisca process. Referring to Fig. 3.6, the sized feed coal (generally 1/2 in. x 0) is fed by screw feeders through a rotary valve to the conditioner vessel where the coal is mixed with the parting liquid and the additive. The conditioning of the coal is generally accomplished in a few minutes after the coal is slurried and mildly agitated. The coal-medium slurry is then taken to the center of the separator where the reject material sinks to the bottom of the vessel while the cleaned coal is removed from the top of the vessel by means of a screw conveyor. The cleaned coal is then dried by indirect heat exchange with 200°F water and is taken to product storage. The reject material is removed from the bottom of the separator vessel and is also dried by indirect heat exchange with hot water. The reject material contains about 12% moisture and can be readily compacted for disposal purposes.

As shown in Fig. 3.6, the medium vapors from the conditioner, separator, and dryer vessels are collected and taken to the regeneration section. In the regeneration section, they are filtered, compressed, and condensed for

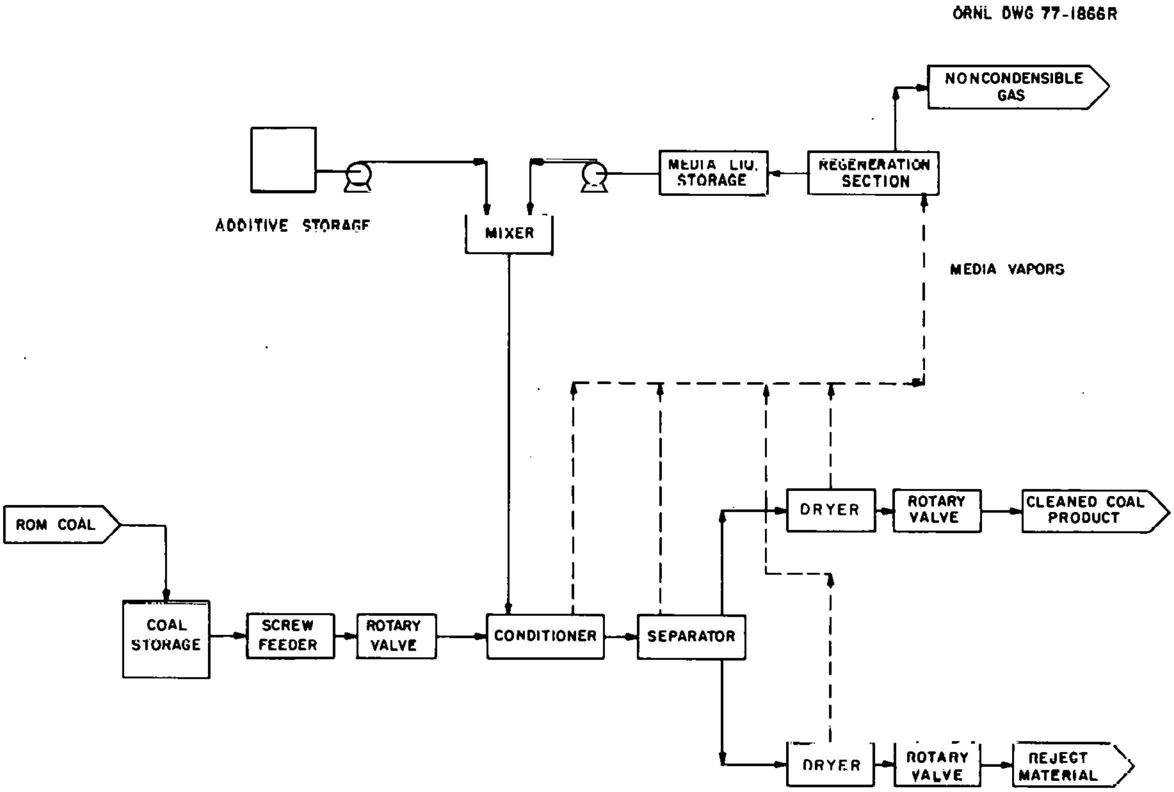


Fig. 3.6. Block flow diagram of the Otisca process.

recycle in the process. The noncondensable gases (consisting mainly of air and water vapor) are stripped from the medium vapors in the regeneration section and are vented to the atmosphere. Parting liquid or medium loss in the process is expected to be less than 2 lb of medium liquid per ton of feed coal. The concentration of the medium vapors in the noncondensables gas stream can be reduced to a few parts per million by processing the noncondensables gas stream through a carbon adsorber or an oil absorber. This may be necessary to avoid problems related to the discharge of Freon into the atmosphere. Concentration of the medium in the cleaned coal product and the reject streams (downstream of the dryers) is expected to be on the order of a few parts per million.

3.6.3 Economics of the process

Time limitations for the present beneficiation study precluded an independent economic evaluation of the process. However, according to ref. 23, the developers of the process indicate that the capital investment for a battery-limits facility is about $10,000 per ton per hour of feed coal processed, whereas the operating costs are estimated to be less than $1 per ton of feed coal processed. The operating costs given above are stated to include the cost of the operating and maintenance labor, the process and maintenance materials, and the plant energy requirements. No costs were included for the use of capital, taxes, and depreciation. As indicated earlier, the operating cost reported appears to be very low.

The developers claim that the capital cost for a similar size water-based coal beneficiation facility is expected to be 2 to 4 times the capital cost for the Otisca plant.[23]

It is expected that an independent evaluation of the process can be performed at a later date to verify the claims of the process developers.

3.6.4 Conclusions and recommendations

Based on the results of the evaluation presented in this report, the following conclusions can be made regarding the Otisca process:

1. It is a relatively simple process.

2. It uses a medium (for the beneficiation) that is relatively innocuous in terms of its toxicity, flammability, and corrosive characteristics.
3. The process plants will be designed to be completely enclosed. Hence, noise and air pollution problems are expected to be reduced considerably.
4. Because of the noncorrosive nature of the medium used and the mild processing conditions, no special materials of construction are required for fabricating the process equipment.
5. The process is claimed to efficiently beneficiate a wide range of coal size consists. It appears to be applicable even for processing fine-sized (200 mesh x 0) coal.
6. Maintenance costs for the plant are expected to be low.
7. Since Freon (a fluorocarbon) is used as the parting liquid in the process, it may pose an environmental problem. In recent times, concern has been expressed regarding the potentially deleterious effect of fluorocarbons discharged into the earth's atmosphere.
8. The process can only reduce the ash and the pyritic sulfur contents of the coal; it does not affect the organic sulfur content of the coal. Hence, the same regional considerations apply to the Otisca process as apply to several of the other coal beneficiation processes discussed in this report. That is, if the processing plant is built as a mine-mouth facility, then its potential applicability is restricted to those regions of the country that have low-organic-sulfur-content coal. However, if the plant is built at the end-use site, the above regional limitations do not apply.

Overall, the process appears to possess considerable merit. It appears to be a simple, versatile, and inexpensive process. However, to more fully explore the applicability of the process, it is recommended that:

1. a more detailed evaluation of the process be conducted (preferably by an independent organization or person) to determine the merits and limitations of the process, and

2. further process developments be supported to determine the range of applicability and the commercial viability of the process.

3.7 Wet High-Gradient Magnetic Separation Process

3.7.1 Introduction

The wet high-gradient magnetic separation (HGMS) process has been proposed as a method for reducing the pyritic sulfur and ash contents of coal. The process relies on the difference in the magnetic susceptibility of the coal and the mineral impurities to effect the separation between them. The process is based on a commercially proven process that is used in the kaolin industry to remove iron and titanium impurities from kaolin clay.

Basically, the process involves passing a water slurry of finely pulverized coal [generally -200 mesh (-74 μm) particle size] at ambient temperature and pressure through a container where it is subjected to a high-intensity magnetic field (field intensity up to 20 kOe). The container is generally packed with a stainless steel wool matrix. The paramagnetic material present in the coal slurry, such as pyrite and mineral matter, becomes magnetized and is trapped in the matrix while the diamagnetic coal particles, unaffected by the magnetic field, pass through the container for further downstream processing. When the steel wool matrix is loaded to its magnetic capacity, the slurry feed is stopped and the electric power is cut off. The matrix is then backwashed to remove the trapped pyrite and ash. Following the backwashing step, the feed and the power are resumed to the HGMS container, and the entire process is repeated. Power consumption for generating the high-intensity magnetic field in a single HGMS unit is estimated to be 400 to 500 kW, and a single unit can clean up to 100 tons/hr of feed material.[24]

The process is relatively simple and efficient. Results of experiments reported by Liu and Lin[25] indicate that, depending on the type of coal and experimental conditions used, a single pass through an HGMS device reduces the pyritic sulfur content of the coal by 80 to 90%, the ash content by 35 to 45%, and the total sulfur level by 40 to 55%. These reduction levels were obtained while achieving about 95% recovery of the coal. Other investigators in the field have reported obtaining similar results using HGMS separators.

The process can be used to reduce the sulfur level of coals having a high pyritic sulfur content. However, since the process is inherently a mechanical beneficiation type process, the coal passes through the process virtually unchanged. Hence, the process would not be suitable for reducing the sulfur level of coals that have a high organic sulfur content and a low pyritic sulfur content. Other drawbacks of the process at the present stage of development are:

1. The process is batch or cyclic in nature. This entails either considerable downtime for backwashing the magnetic filter or the installation of several HGMS separators in parallel to permit continuous operation of the process.
2. The coal has to be pulverized to a fine size to permit the liberation of the pyrite and the ash from the coal. This increases the cost of pulverizing and, more importantly, dewatering the product coal.

Preliminary economic estimates reported by Murray[24] indicate that the installed capital cost for a 500-ton/hr HGMS coal cleaning plant would be about $8 million, and the operating costs were reported to be $0.37 per ton of clean coal produced. The above costs appear to be very low; however, time limitations for the present beneficiation study precluded an independent evaluation of the economics of the HGMS process.

Studies are currently being conducted to develop a continuous version of the process, which would use a moving matrix HGMS unit called the Carousel Separator.[26] Efforts are also under way to replace the stainless steel wool matrix with other matrix types to permit the beneficiation of coarser feed materials.

Most of the studies on HGMS technology have been conducted in bench- or pilot plant-scale equipment. However, much development work remains to be done in semicommercial-scale units before the process can even be considered to be a commercially viable process.

3.7.2 Process description

Figure 3.7 is a conceptual flow diagram of the commercial version of the process with a schematic of the high-intensity magnetic separator. Referring to Fig. 3.7, ROM coal is first mechanically crushed to -200 mesh (-74 μm) size to liberate as much of the pyrite and ash from the coal as possible. The finely pulverized coal is then taken to a mixing tank where it is mixed with water and a very small amount of dispersant or wetting agent to form a 30 wt % coal slurry. The wetting agent is added to minimize froth formation. The coal slurry is then pumped into the HGMS container at a fixed rate where it is subjected to a high-intensity magnetic field (~20 kOe). At present, the container vessel can be up to 7 ft (~2.1 m) in diameter and about 20 in. (~51 cm) tall. The vessel is packed with stainless steel wool (or other suitable material) to form a matrix with a void volume of about 94 to 95%. The pyritic sulfur and the ash constituents in the coal slurry become magnetized and are trapped on the steel wool matrix while the coal passes through the separator unaffected. The cleaned coal slurry is taken through a filtration step such as a vacuum filter where excess water is removed from the coal. The moist coal then passes through a thermal dryer where it is dried to the desired moisture content to yield the cleaned product coal. Water that is separated from the coal in the filter is clarified and reused.

The coal slurry is allowed to flow through the HGMS until the matrix reaches its magnetic loading capacity. When this point is reached, the feed is stopped and the power is switched off. The magnetic filter is then backwashed with water to remove the trapped pyrites and mineral matter. With the magnetic field switched off, the mineral matter is released from the matrix quite readily. The effluent water from the backwashing step is taken to a clarifier or settling tank where the water is recovered for reuse; the mineral matter collected is disposed of. After the magnetic filter has been washed clean, the slurry feed to the HGMS is resumed, and the entire process is repeated in a cyclic manner.

In normal industrial operations, it is envisaged that several of these HGMS units may be used in parallel so that, while one is being backwashed, the slurry can be fed to the others or, alternatively, the coal

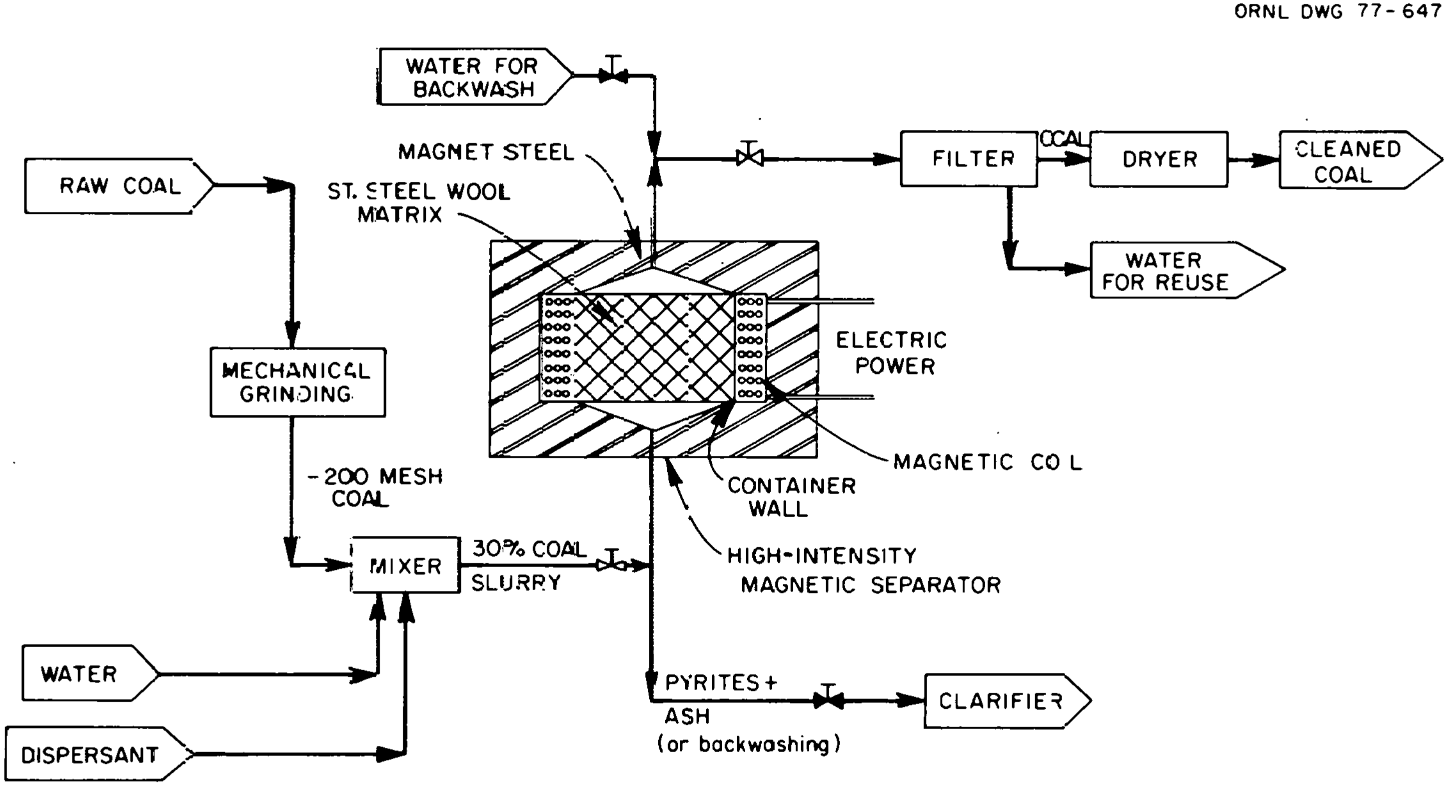


Fig. 3.7. Block flow diagram of the high-gradient magnetic separation process.

beneficiation plant may be built around a Carousel-type HGMS unit mentioned earlier.

3.8 Oil Agglomeration Process

3.8.1 Introduction

The oil agglomeration process or the spherical agglomeration process[27] is a wet mechanical beneficiation process that beneficiates the coal by forming microagglomerates or flocs of the coal particles. The process has been developed up to the semipilot-plant scale level by the National Research Council of Canada. The Trent,[28] Convertol,[29] and Central Fuel Research Institute of India (CFRI) oil agglomeration processes[30] use the same principles as the oil agglomeration process described here. The process is especially suited for the beneficiation of fine-sized coals and yields the best results when used with other wet mechanical beneficiation processes such as heavy-medium or gravity separation. The process may be used either as an alternate to the froth flotation process or as an additional processing step following froth flotation to recover the very fine-sized (<200-mesh) coal particles that are generally not recovered by the froth flotation process.

The process basically consists of recovering or upgrading the fine coal particles, when they exist as a suspension in water, by using a second liquid such as kerosene or fuel oil that is immiscible with water. The second liquid preferentially wets the fine coal particles and causes them to agglomerate or flocculate. The fine coal-water-oil mixture is then taken through a sink-float step where the coal flocs float on the water while the associated mineral matter and pyrites, being hydrophilic, sink to the bottom of the tank. The flocs are then removed and pelletized into larger sized-balls to improve their mechanical properties. Capes et al.[31] report that their laboratory tests indicated that:

1. The process can reduce the ash and the total sulfur content of the coal by about 76 and 56%, respectively, while recovering about 90% of the potential heat content of the coal. The reduction in the total sulfur content is due to the reduction in the pyritic sulfur content of the coal. The organic sulfur content is not affected by the process.

2. The process is most effective when operated as a two-step process in which one liquid (generally a light oil) is used to effect the separation of the fine coal from the mineral matter while a second liquid (generally a heavier oil) is used to pelletize the flocs to improve their mechanical properties.

3. Of the several liquids investigated as the agglomerating oil, Varsol (a kerosene-like petroleum distillate) appeared to give the best results. Other liquids tested were fuel oil, kerosene, light coal tar, and heavy crude oil.

3.8.2 Process description

Figure 3.8 is a sketch of the conceptual commercial-scale version of the process. The pulverized coal (-28 mesh) is mixed with water to form a 20 wt % coal-water slurry. The coal-water slurry is mixed with the agglomerating oil in high-shear mixers where the coal particles are preferentially wetted by the oil. The slurry-oil mixture is then transferred to agglomeration and settling tanks where the carbonaceous material is skimmed from the surface as flocs while the mineral matter and the liberated pyrites sink to the bottom of the vessel. The skimmed flocs are transferred to dewatering screens where the excess water is drained. The dewatered flocs are then taken to a pelletizing disc where heavy pelletizing oil is added to the flocs to form large-sized (generally >1/4 in. in diameter) pellets. These pellets are shipped as the cleaned coal product from the plant.

The mineral matter and the pyrites (tailings) that were separated from the coal in the agglomeration and settling tanks and the water from the dewatering screens are taken through a hydrocyclone where the tailings are rejected; the water is recovered and recycled in the process. The tailings are discarded as plant refuse.

3.8.3 Conclusions and recommendations

Based on the results of the above study, the following conclusions can be made regarding the oil agglomeration process:

1. The process is applicable only to fine-sized coal.

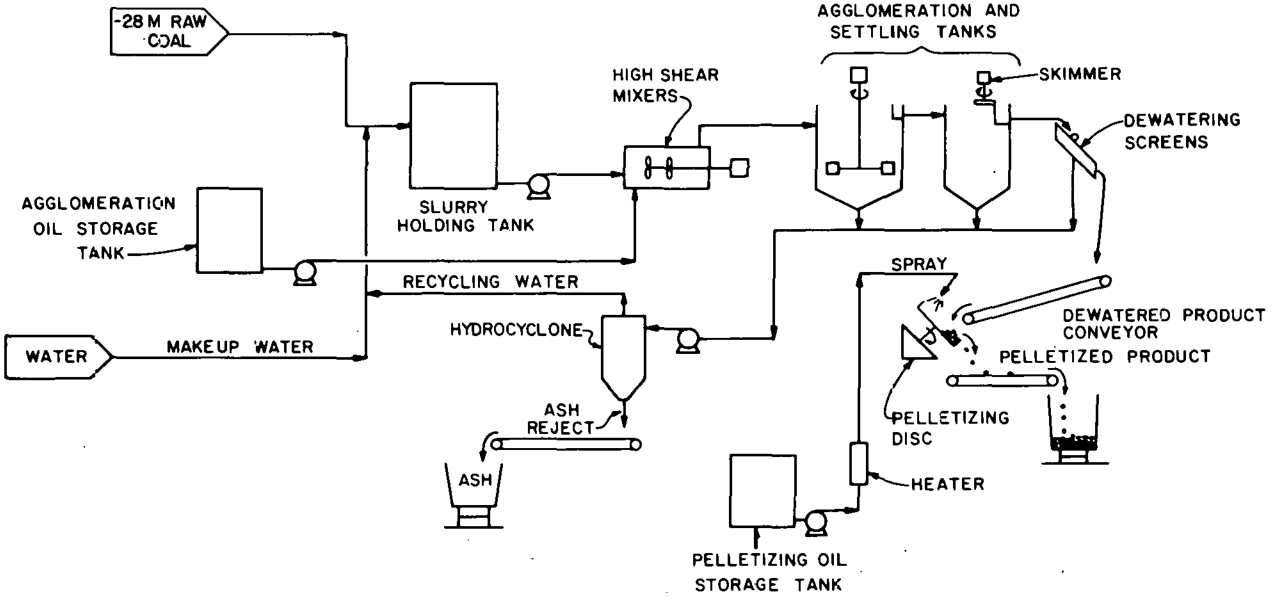


Fig. 3.8. Diagrammatic sketch of the NRCC oil agglomeration process.

2. It is a relatively simple process and yields a cleaned coal product with improved handling properties.
3. The use of the oil helps to reduce the dewatering costs considerably.
4. The process yields best results when used in conjunction with other mechanical beneficiation processes. It should be considered as an alternate to the froth flotation process.
5. The process can apparently be tailored to handle any type of coal by a judicious selection of the agglomerating oil.
6. The process is most applicable when beneficiating easily friable coals.

The following recommendations are made for further studies regarding the oil agglomeration process:

1. The economics of the process should be developed for two cases — namely, where the process is treated as an add-on process to an existing coal preparation facility, and where the process is treated as a stand-alone coal beneficiation facility.
2. Laboratory tests should be continued to determine the range of applicability of the process (in terms of the different types of coal it can beneficiate) and the degree of beneficiation that can be obtained with the process.

4. CHEMICAL BENEFICIATION PROCESSES

4.1 The TRW-Meyers Coal Desulfurization Process

4.1.1 Introduction

The TRW-Meyers coal desulfurization process is a chemical beneficiation process in which the coal is treated with an aqueous ferric sulfate solution at temperatures ranging between 194 and 266°F (90 and 130°C) and pressures up to 120 psig (~0.9 MPa). The coal matter goes through the process virtually unchanged, but the pyritic sulfur present in the coal is leached out by the ferric sulfate solution to form ferrous sulfate and elemental sulfur.

The ferric sulfate consumed in the process is continuously regenerated by reacting the spent leach solution with oxygen or air. Excess ferrous sulfate generated in the process is separated out and may be recovered as a by-product of the process. The elemental sulfur formed in the reaction is also recovered by either steam distillation or solvent extraction as a by-product of the process. The underlying chemistry of the process may be represented by the following stoichiometric equations:

Treating reaction

$$FeS_2 + 4.6\ Fe_2(SO_4)_3 + 4.8\ H_2O \rightarrow 10.2\ FeSO_4 + 4.8\ H_2SO_4 + 0.8\ S, \quad (1)$$

Regeneration reaction

$$2.4\ O_2 + 9.6\ FeSO_4 + 4.8\ H_2SO_4 \rightarrow 4.8\ Fe_2(SO_4)_3 + 4.8\ H_2O, \quad (2)$$

Net overall reaction

$$2.4\ O_2 + FeS_2 \rightarrow 0.2\ Fe_2(SO_4)_3 + 0.6\ FeSO_4 + 0.8\ S. \quad (3)$$

The process is especially suited to processing coals containing a high percentage of pyritic sulfur. The process is capable of removing up to 95% of the pyritic sulfur present in the coal and of reducing the ash content of the feed coal by 10 to 30%. In so doing, the process can yield a product coal that has up to 5% higher heating value than the feed coal.

Working under EPA sponsorship, TRW has conducted extensive laboratory and bench-scale tests over the past six years to develop the process. Though the process itself is new, it is based on established unit operations practiced in the ore-dressing and steel industries. An 8-ton/day process development unit was expected to be ready by mid-1977 to demonstrate key steps in the process and to verify the commercial viability of the process.

4.1.2 Process description

The TRW-Meyers coal desulfurization process was initially developed for beneficiating fine coals with a nominal top particle size less than 1/16 in. (-1.4 mm), which corresponds to a nominal top size less than 14 mesh in the U.S. Sieve Series. However, later process development efforts at TRW indicated that the process can be engineered to desulfurize coarse coals having a nominal top size of 1/4 in. (6.4 mm). Processing fine coals results in the highest rate of pyritic sulfur removal from the coal. However, the dewatering costs are higher, and the product coal may have to be pelletized to avoid excessive windage loss if the product coal has to be shipped. Coarse coal processing, on the other hand, has a much slower rate of sulfur removal, but, generally, the dewatering costs are lower and the coal can be shipped directly over long distances without requiring pelletizing.

The processing scheme to be used in any given situation will, of course, depend primarily on the pyritic sulfur level of the ROM coal, the degree or depth of cleaning required, and the end use of the cleaned product coal. Brief descriptions of both the fine and the coarse coal processing schemes are presented below.

4.1.3 Fine coal processing scheme

Figure 4.1 is a block flow diagram of the fine coal processing scheme. Referring to Fig. 4.1, ROM coal is first ground to a nominal top size of less than 14 mesh U.S. Sieve Series (USS). The pulverized coal is then intimately mixed with the hot recycled leach solution in the mixing vessel. The coal-leach solution slurry is transferred to the reaction/regeneration reactors where the pyrite-leaching reaction is permitted to occur for about 8 hr at temperatures ranging between 215 and 265°F (~102 and 130°C) and pressures up to 8 atm (0.9 MPa). The heat of reaction is used to heat the recycle leach solution. The majority of the pyrites present with the coal undergo the treating reaction given by Eq. (1) during this 8-hr period. High-purity oxygen is also added to the reaction mixture to simultaneously regenerate the ferric sulfate leach from the spent ferrous sulfate solution, as shown by Eq. (2).

After about 8 hr the reaction mixture is transferred to the secondary reactor where the residual pyrites in the coal are converted to ferrous sulfate. In the secondary reactor, the leaching reactions occur at the boiling point temperature of the solution and at essentially atmospheric pressure. The coal-leach solution slurry is kept in the secondary reactor for up to 36 hr to permit the depyritization reaction to be completed.

From the secondary reactor, the coal slurry is taken to the wash section where the pulverized coal is separated from the spent leach

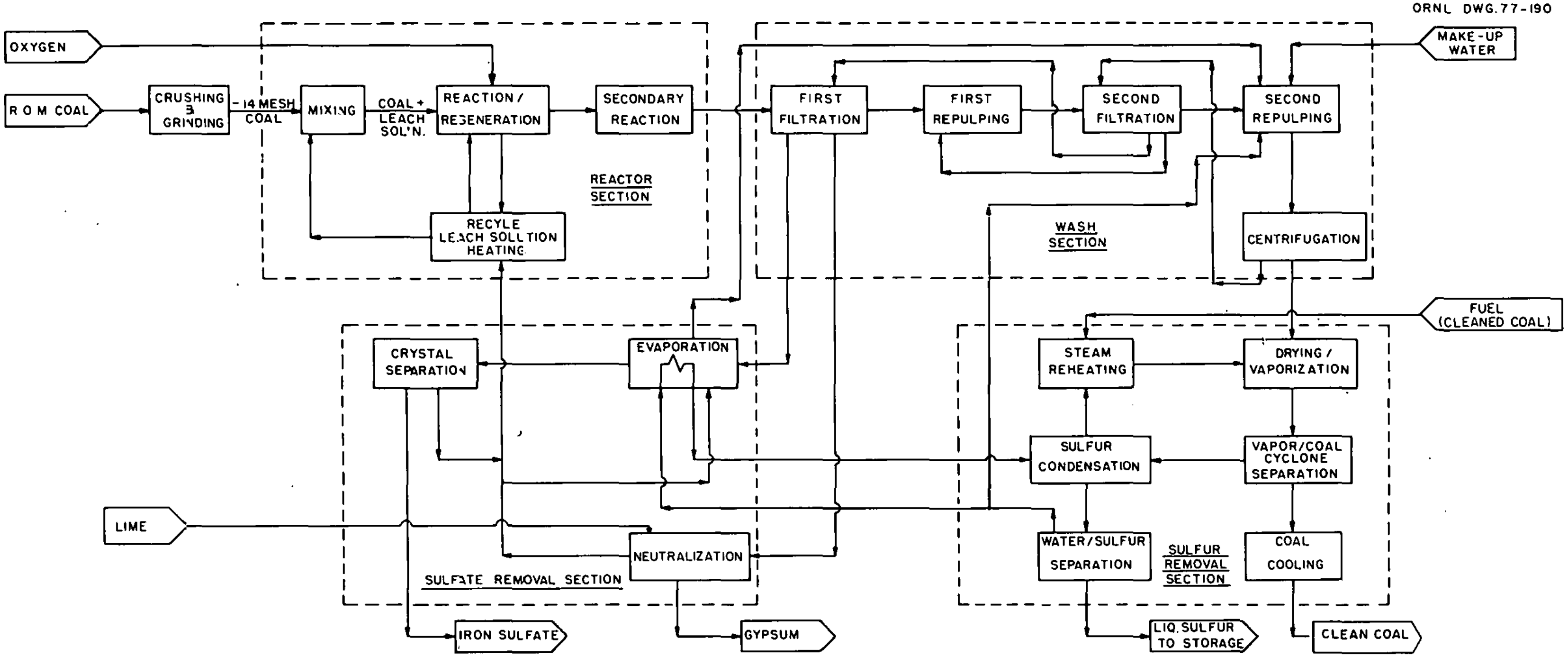


Fig. 4.1. Block flow diagram for the TRW-Meyers fine coal processing scheme.

solution. The filter cake is reslurried and refiltered to remove as much of the leach solution as possible. Cleaner water (that is, water containing a lower concentration of the spent leach solution) is used to wash the filter cake and reslurry it at each succeeding step. After the coal has been slurried for the second time, the coal cake is dewatered in a centrifuge.

Moist coal from the centrifuge is then taken to the drying/vaporization step where the coal cake is flash dried by high-temperature steam, which is provided from the steam reheating step. Flash drying the coal also vaporizes the elemental sulfur accompanying the coal from the treating reaction. The dried coal is separated from the steam-sulfur vapor stream in a cyclone separator and is cooled to yield the cleaned product coal. If required, the clean coal may then be pelletized for long-distance shipment.

The steam-sulfur vapor stream that is separated from the coal in the cyclone separator is taken to the sulfur condensation step where it is scrubbed with hot recycle water. In this step, the sulfur vapor is condensed to yield the liquid sulfur product, and the hot water is vaporized to form steam,which is then externally heated and used to flash dry the moist coal cake in the drying/vaporization step mentioned earlier. The hot liquid sulfur and the condensed water are taken to the water/sulfur separation step where the liquid sulfur is separated from the water in a phase separator. The liquid sulfur is removed from the phase separator and is taken to storage as a salable by-product of the process. The hot water from the phase separator is used to provide the heat duty in the triple-effect evaporator in the sulfate removal section and is subsequently returned to the sulfur condensation step for reuse.

The filtrate and the wash water from the first filtration step in the wash section are rich in ferrous sulfate. This stream is concentrated in a triple-effect evaporator located in the sulfate removal section. The wash water recovered from the evaporators is reused in the second repulping step. The concentrated liquor from the evaporators is taken to the crystal separation step where the iron sulfate crystals are separated from the leach solution. The iron sulfate crystals are stored for possible reuse in the process or are disposed of as waste products. If a market should exist for the iron sulfate, the crystals can be sold as a by-product of the process. However, the iron crystals are generally disposed of as plant waste.

A portion of the wash water from the first filtration step in the wash section is neutralized by the addition of lime to yield gypsum. Just like the iron sulfate crystals mentioned above, the gypsum produced may be disposed of either as a by-product of the process or as a plant waste stream.

The neutralized wash water from the neutralization step is combined with the concentrated leach solution from the crystal separation step and is returned to the reactor section for reuse.

The process is relatively self-sufficient in that the leachant is generated in the process. Most of the plant streams from the various unit operations are recycled as far as possible. Oxygen and lime are the only chemicals used in the process other than some make-up water which is needed to replace the water lost in the vacuum filters and the evaporator. Some fuel is also required to heat the steam used in the flash drying step. A small fraction of the cleaned product coal is generally used to meet the plant fuel requirements.

A sketch of the baseline flow diagram for the conceptual commercial-scale embodiment of the TRW-Meyers fine coal processing scheme is given in Fig. 4.2.

4.1.4 Coarse coal processing scheme

As indicated earlier, some of the major incentives for developing the coarse coal processing scheme are:

1. less preleaching preparation of the coal,
2. lower costs for dewatering the cleaned coal, and
3. elimination of briquetting or pelletizing the cleaned product coal.

The disadvantage of the coarse coal processing scheme is that the leaching reaction rates are considerably slower, thereby necessitating much longer coal processing times.

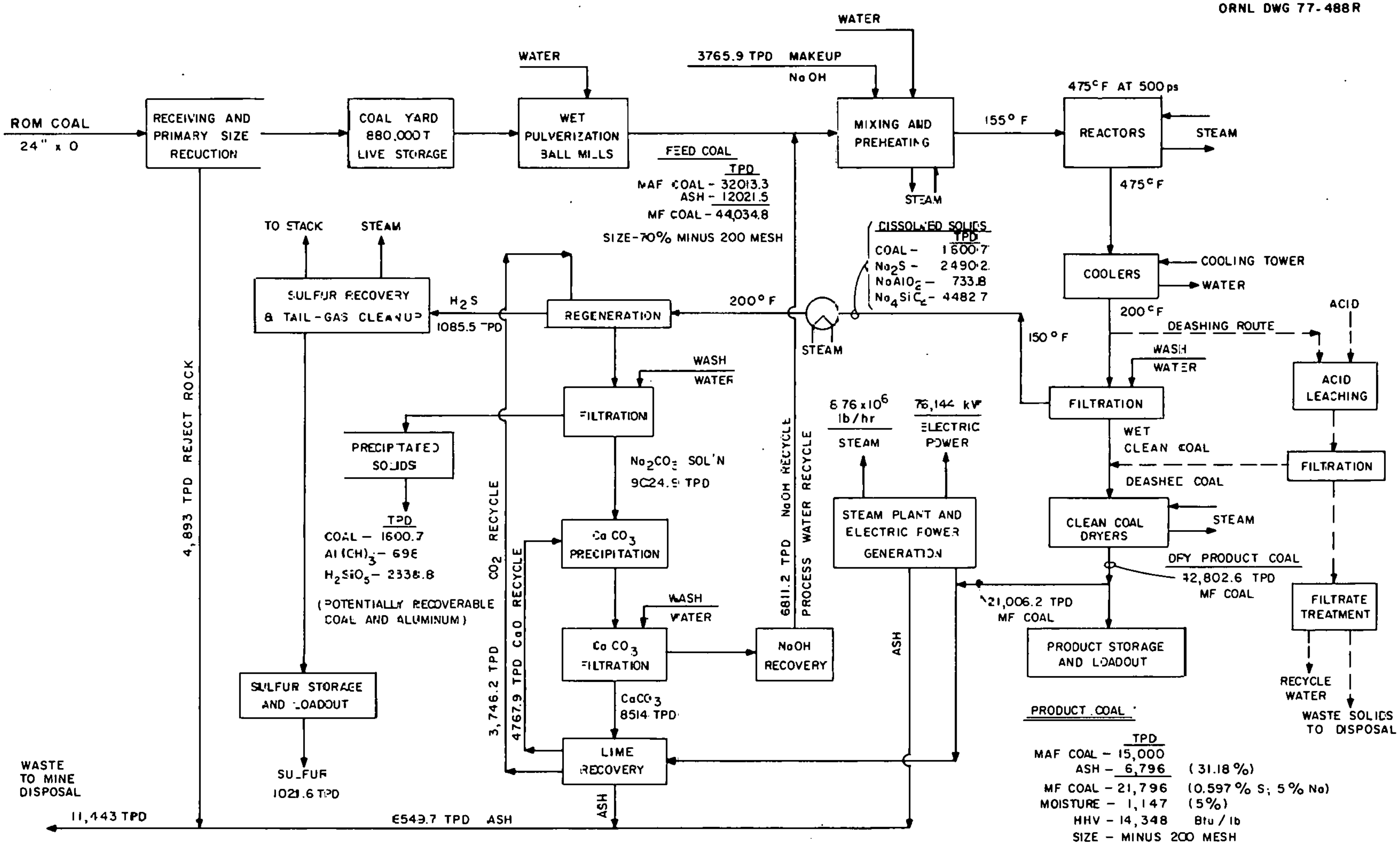


Fig. 4.2. Schematic flow diagram for the TRW-Meyers fine coal desulfurization process.

Coarse coal processing is carried out at approximately atmospheric pressure because studies at TRW indicated that pressure does not significantly increase the pyrite leaching rate from coarse coals.

The nominal coal particle size for coarse coal processing is 1/4 in. x 0 (6.35 mm x 0). The fine coal processing scheme described earlier cannot be readily applied to processing coarse coals because of the tendency of the coal to separate out of the leach solution. Though the fines in the above size consist (nominally 48 mesh x 0) can be slurried, the larger-size coal (that is, 1/4 in. x 48 mesh) settles out of the leach solution quite rapidly. To circumvent this problem, the coal mass is held in a fixed position (as in a packed bed) and the leach solution is percolated through the coal mass. In this processing scheme, the coal is transferred from one operation to the next by means of mechanical conveyor systems rather than by slurry pumping.

TRW extensively evaluated the following possible reactor configurations:

1. above-ground batch reactor,
2. lined pit batch reactor,
3. continuous cocurrent reactor, and
4. continuous countercurrent reactor.

Their studies indicated that reactor configurations 2 and 4 are the optimum configurations. Either of the two reactor configurations may be used for processing coarse coals.

Figure 4.3 is a block diagram of the conceptual coarse coal processing scheme. Referring to Fig. 4.3, coal crushed to 1/4 in. x 0 size consist is fed to the ambient-pressure reactor. In the reactor the coal is contacted with freshly regenerated leach solution from the leach solution regenerator. The leach solution is rich in ferric sulfate, and the pyrites in the coal undergo the treating reaction given by Eq. (1). The residence time for the coal in the reactor is approximately 50 hr. The exact residence time depends on the pyritic sulfur content of the coal and also on the type of reactor used. Spent leach solution from the reactor is returned to the leach solution regenerator. The spent solution also contains a portion of the fines fraction from the coal.

ORNL DWG.77-188

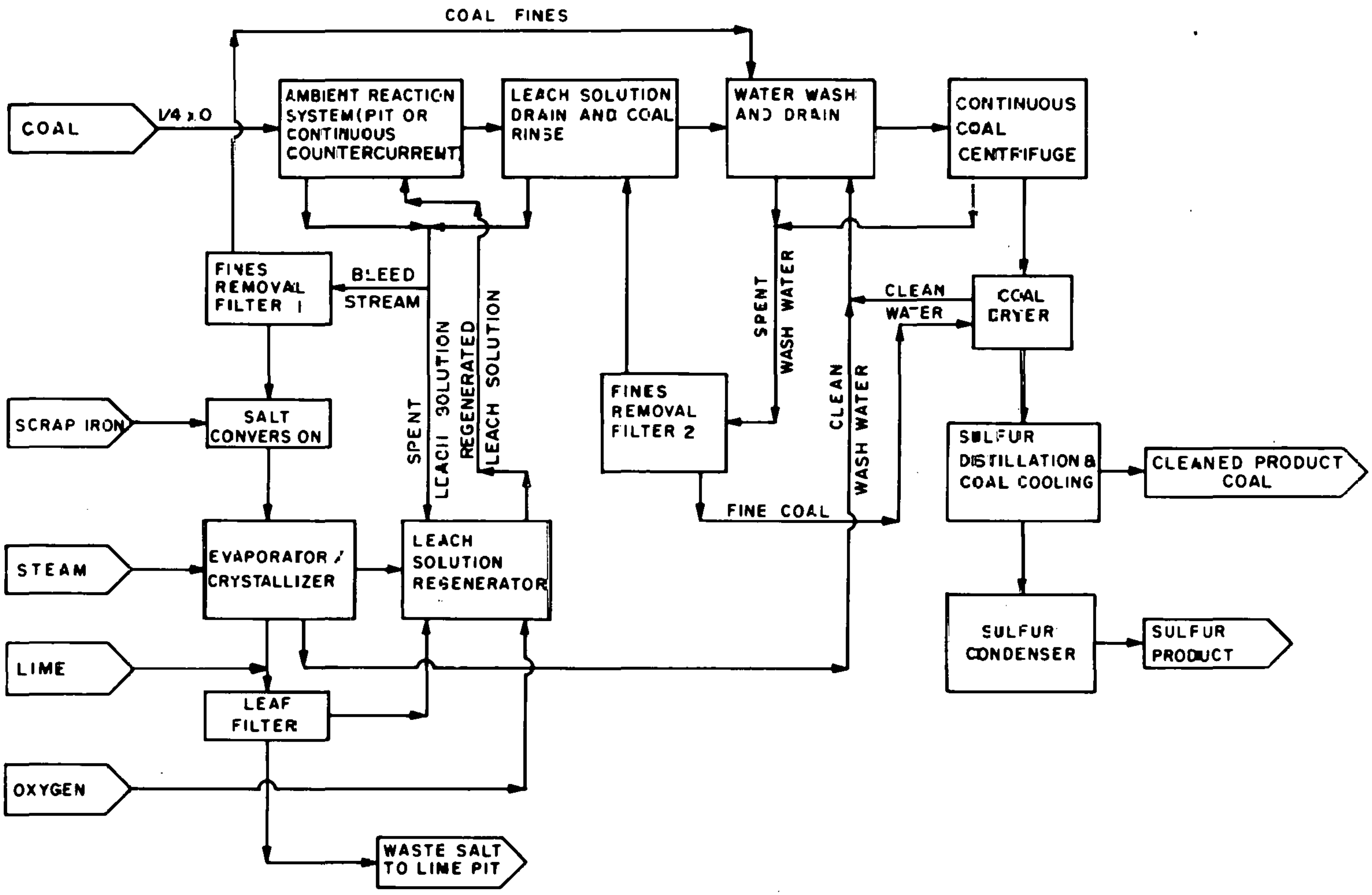


Fig. 4.3. Block flow diagram for the TRW-Meyers coarse coal processing scheme.

After the required reaction period, the leach solution--wet coal is taken from the reactor to the leach solution drain and coal rinse step. In this operation, the leach solution is drained from the coal, and the coal mass is spray-rinsed on a conveyor with leach solution--contaminated water obtained from the fines removal filter 2. Following the draining and the rinsing operation, the coal is transferred by conveyors to the water wash and drain step where the coal is washed with clean water recovered from the evaporator/crystallizer and the coal dryer. The wash vessel is sized to allow 1-hr residence time for the coal to permit the water to wash off the leach solution present in the coal pores. The water is then drained from the coal, and the coal moisture content is reduced to 20 to 25%. The moist coal then moves to an inert-atmosphere dryer where the coal is dried to the desired moisture level.

From the dryer, the coal moves to the sulfur distillation step from where the elemental sulfur formed during the leaching process is distilled. The cleaned coal is then cooled and taken to storage for eventual sale. The sulfur vapors removed in the sulfur distillation step are condensed and cast into blocks for disposal as a salable by-product of the process.

The spent leach solution stream from the ambient reactor is combined with the liquid stream recovered from the leach solution drain step and is taken to the leach solution regenerator where the ferrous sulfate is reacted with oxygen according to the regeneration reaction given by Eq. (2).

The combined feed stream to the leach solution regenerator contains a portion of the fines fraction from the feed coal. A bleed stream is withdrawn from this stream and is taken to fines removal filter 1 where the fine coal is filtered from the weak, spent leach solution. The fine coal cake from the filter is returned to the main coal stream at the water wash and drain step. The filtrate from the filter is taken to the salt conversion step where a major fraction of the ferric ions is converted to ferrous ions by the addition of scrap iron. The effluent stream from the salt conversion step is taken to the evaporator/crystallizer where the water is evaporated from the stream. The clean water from the evaporator/crystallizer is mixed with the clean water from the dryer and is taken to the water wash and drain step where it is used to wash out the residual leach solution from the coal. The concentrated mother liquor from the evaporator/crystallizer is neutralized by the addition of lime and is then filtered through a leaf filter. The crystallized salts from the filter are disposed of as waste salt, while the filtrate is taken to the leach solution regenerator for eventual reuse in the process.

Spent wash water from the water wash and drain step is filtered through fines removal filter 2. The fine coal cake from the filter is taken and dried with the main coal stream in the dryer, while the filtrate is used as the rinse water in the leach solution drain and coal rinse step.

4.1.5 Mass and energy balances

Simplified mass and energy balances were developed for the two premised conceptual beneficiation plant sizes (namely, 1500 and 15,000 tons/day of maf product coal) based on the information reported by TRW in the EPA report.[32] The balances were developed for the three coals in the subset of representative coals (Pennsylvania, western Kentucky, and Illinois). The results of the analyses are summarized in Tables 4.1 and 4.2 for the grassroots and the battery-limits type facilities.

4.1.6 Economic evaluation

Detailed economic analyses using the DCF method have been performed for the TRW-Meyers fine coal processing scheme. The analyses were carried out for conceptual plants designed to produce 1500 and 15,000 tons/day of maf coal. The basic premises underlying the economic analyses are given in Appendix A. Order-of-magnitude type costs were developed for the processing plants based on information reported by TRW in EPA Report No. EPA-600/2-76-143a.[32] TRW reported the economics based on costs effective in June 1975. In the present study, the TRW costs have been escalated using the appropriate Marshall and Swift escalation factors obtained from Chemical Engineering[33] to reflect costs effective in January 1977.

Results of the economic analyses are summarized in Table 4.3 for the coals and plant types evaluated, together with the calculated product coal prices for the 12 and 15% annual after-tax rate of return (AARR) on equity capital. The results of the analyses have also been plotted as graphs of the cleaned product coal price for ROM coal costs ranging between $10 per

Table 4.1. TRW-Meyers fine coal processing scheme summary

Facility type: grassroots

	1500-ton/day facility						15,000-ton/day facility					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	2339	1701	1975	1675	2085	1705	23,323	16,963	19,745	16,744	20,843	17,039
Ash, %	27.3		15.2		18.25		27.3		15.2		18.25	
Total sulfur, %	2.90		2.55		4.21		2.90		2.55		4.21	
Total moisture, % (assumed)	10.0		10.0		10.0		10.0		10.0		10.0	
HHV, Btu/lb		15,194		14,367		13,877		15,194		14,367		13,877
B. Clean coal product	1919	1500	1699	1500	1752	1500	19,173	15,000	16,935	15,000	17,520	15,000
Ash, %	21.8		11.7		14.4		21.8		11.7		14.4	
Total sulfur, %	0.62		1.0		1.82		0.62		1.0		1.82	
Total moisture, % (premised)	5.0		5.0		5.0		5.0		5.0		5.0	
HHV, Btu/lb		15,194		14,367		13,877		15,194		14,367		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		51.68		48.14		47.32		515.5		481.1		472.9
Clean coal product		45.58		43.10		41.63		455.8		431.0		416.3
Percent recovery												
Material[a]	82.0		86.0		84.0		82.1		86.0		84.0	
Thermal[b]		88.2		89.5		88.0		88.4		89.6		88.0
Beneficiation cost[c,d]												
$ per ton	12.43		13.97		13.52		7.30		8.21		7.88	
¢ per million Btu		54		57		59		32		34		34

[a] Material recovery = $\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}} \times 100.$

[b] Thermal recovery = $\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}} \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 4.2. TRW-Meyers fine coal processing scheme summary

Facility type: battery-limits

	1500-ton/day facility						15,000-ton/day facility					
	Pennsylvania		Western Kentucky		Illinois		Pennsylvania		Western Kentucky		Illinois	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	2274	1653	1920	1628	2027	1657	22,731	16,525	19,196	16,278	20,264	16,566
Ash, %	27.3		15.2		18.25		27.3		15.2		18.25	
Total sulfur, %	2.90		2.55		4.21		2.90		2.55		4.21	
Total moisture, % (assumed)	10.0		10.0		10.0		10.0		10.0		10.0	
HHV, Btu/lb		15,194		14,367		13,877		15,194		14,367		13,877
B. Clean coal product	1919	1500	1698	1500	1752	1500	19,190	15,000	16,985	15,000	17,519	15,000
Ash, %	21.8		11.7		14.4		21.8		11.7		14.4	
Total sulfur, %	0.62		1.0		1.82		0.62		1.0		1.82	
Total moisture, % (premised)	5.0		5.0		5.0		5.0		5.0		5.0	
HHV, Btu/lb		15,194		14,367		13,877		15,194		14,367		13,877
Potential thermal energy (10^9 Btu/day)												
Raw coal feed		50.23		46.78		45.99		502.2		467.7		459.8
Clean coal product		45.58		43.10		41.63		455.8		431.0		416.3
Percent recovery												
Material[a]	84.4		88.5		86.4		84.4		88.5		86.5	
Thermal[b]		90.8		92.1		90.5		90.8		92.2		90.5
Beneficiation cost[c,d]												
$ per ton	12.06		13.29		13.13		7.99		8.64		8.62	
¢ per million Btu		53		55		57		35		35		38

[a] Material recovery = $\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}} \times 100.$

[b] Thermal recovery = $\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}} \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

Table 4.3. Summary of economic analyses for the conceptual TRW-Meyers fine coal beneficiation plants[a]
Plant size, in tons/day of maf product coal

	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
Component	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Cost, millions of dollars												
Direct capital	17.73	122.94	17.58	121.86	17.78	123.12	11.63	81.96	11.53	79.88	11.65	80.72
Annual operating (gross)[b]	4.57	23.03	4.55	22.87	4.58	23.05	5.43	34.03	5.26	33.12	5.47	34.01
Working capital	3.18	29.86	2.83	26.45	2.93	27.39	3.24	30.67	2.88	27.09	2.99	28.19
Total capital investment	26.58	183.54	26.04	178.78	26.41	181.29	18.88	139.45	18.40	133.13	18.67	135.34
Product coal price, $ per ton[c]												
At 12% AARR[d]	37.60	32.44	38.14	32.36	38.21	32.56	36.52	32.44	36.78	32.12	37.13	32.62
At 15% AARR	38.21	32.90	38.81	32.86	38.87	33.06	36.95	32.79	37.25	32.50	37.60	32.99

[a] The beneficiation plants were designed to operate 3 shifts/day, 7 days/week with 90% annual plant service factor.

[b] For 90% plant service factor.

[c] Calculated product coal price based on $20 per ton ROM coal, 70:30 debt/equity ratio, and 9% annual interest rate on debt fraction of capital. This price includes the ROM coal cost.

[d] AARR = annual after-tax rate of return on equity capital.

ton and $50 per ton and for debt/equity ratios of 0:100, 30:70, 70:30, and 95:5. These plots for the 12 and 15% AARR cases are shown in Appendix B.

The calculated annual operating cost, working capital, and the capital investment for the conceptual plants are summarized in Tables 4.4, 4.5, and 4.6, respectively. Table 4.7 lists the offsite facilities included in the above cost estimates.

Detailed economic analyses for the coarse coal processing scheme (similar to those reported above for the fine coal processing scheme) have not been performed. However, the TRW studies presented in the EPA report[32] indicate that, for the coarse coal processing scheme, the capital investment requirements are about 50% lower and the operating costs are about 25% less than similar costs for the fine coal processing scheme. Detailed analyses of the coarse coal processing scheme are proposed to be conducted contingent upon the availability of time.

4.1.7 Materials of construction

Experimental studies were conducted at TRW to determine the materials of construction that may be used to fabricate the equipment used in the TRW-Meyers coal desulfurization process. These studies consisted largely of static testing of various stainless steel alloys in environments simulating the leaching chemicals used in the process with some short-duration dynamic testing under actual operating conditions. The results of the above studies are presented in the EPA report.[32]

Based on the above study, the following conclusions may be drawn regarding the materials of construction that can be used to fabricate the process equipment:

1. The materials of construction selected must possess the necessary mechanical strength and abrasion and corrosion resistance dictated by the processing conditions and must be relatively inexpensive.
2. Static testing results indicated that 304, 304L, 316, and 316L stainless steel alloys are marginal as materials of construction for the coal desulfurization reactor.

Table 4.4. Operating cost summary for the conceptual TRW-Meyers fine coal beneficiation facilities

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Utilities[a]												
Electric power at 2.5¢/kWhr	0.0	0.0	0.0	0.0	0.0	0.0	1.197	11.375	1.180	11.207	1.200	11.403
Process water at $0.5/kgal	0.021	0.205	0.020	0.202	0.021	0.205	0.020	0.199	0.020	0.196	0.020	0.200
Cooling water at $0.05/kgal	0.189	1.884	0.187	1.858	0.190	1.883	0.172	1.719	0.169	1.692	0.172	1.724
Chemicals[a]												
99.5% oxygen at $30 per ton	0.0	0.0	0.0	0.0	0.0	0.0	0.510	5.088	0.344	3.437	0.536	5.358
Lime at $28 per ton	0.087	0.869	0.086	0.856	0.088	0.871	0.084	0.844	0.083	0.832	0.085	0.847
Operating labor cost												
Process operating labor	0.995	3.194	0.995	3.194	0.995	3.194	0.990	3.176	0.990	3.176	0.990	3.176
Supervisory personnel cost	0.199	0.639	0.199	0.639	0.199	0.639	0.198	0.635	0.198	0.635	0.198	0.635
Labor burden	0.418	1.341	0.418	1.341	0.418	1.341	0.416	1.334	0.416	1.334	0.416	1.334
Plant maintenance cost (includes maintenance materials, labor, supervision, and maintenance labor burden)	1.153	7.561	1.143	7.495	1.156	7.572	0.755	5.327	0.749	5.192	0.757	5.247
Operating supplies[a]	0.299	0.958	0.299	0.958	0.299	0.958	0.297	0.953	0.297	0.953	0.297	0.953
General administrative overhead cost	0.979	4.685	0.975	4.659	0.980	4.690	0.817	3.784	0.814	3.728	0.818	3.750
Waste disposal cost[a]	0.060	0.604	0.060	0.595	0.061	0.605	0.059	0.587	0.058	0.578	0.059	0.588
Property insurance cost	0.234	1.537	0.232	1.523	0.235	1.539	0.153	1.082	0.152	1.054	0.154	1.065
Total gross operating cost[b]	4.634	23.477	4.614	23.320	4.642	23.502	5.668	36.103	5.470	34.014	5.702	36.280
By-product credit[a]	0.310	3.102	0.211	2.102	0.329	3.271	0.300	3.017	0.202	2.041	0.319	3.182
Total net operating cost[b,c]	4.324	20.375	4.403	21.218	4.313	20.231	5.368	33.086	5.268	31.973	5.383	33.098

[a] The costs shown are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an "a" by the desired service factor to obtain the appropriate annual operating cost.

[b] The costs shown do not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately as a part of the analyses in the computer program PRP.

[c] Further details regarding the costs are presented in Appendix A.

Table 4.5. Working capital summary for the conceptual TRW-Meyers fine coal beneficiation facilities

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Raw coal inventory at $20 per ton (20 days)	1.004	10.013	0.857	8.568	0.902	9.019	0.976	9.753	0.833	8.330	0.877	8.768
Product coal inventory at $30 per ton (30 days)	1.795	17.920	1.596	15.962	1.644	16.444	1.795	17.948	1.596	15.963	1.644	16.444
Gross operating costs (30 days)	0.381	1.930	0.379	1.917	0.381	1.932	0.466	2.967	0.450	2.796	0.469	2.982
Total working capital	3.180	29.863	2.832	26.447	2.927	27.395	3.237	30.668	2.879	27.089	2.990	28.194

Table 4.6. Capital investment summary for the conceptual TRW-Meyers fine coal beneficiation facilities

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Coal component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Battery limits beneficiation plant, E	11.82	81.96	11.72	81.24	11.85	82.08	11.63	81.96	11.53	79.88	11.65	80.72
Offsite facilities (see Table 4.7), 50% E	5.91	40.98	5.86	40.62	5.93	41.04	0.0	0.0	0.0	0.0	0.0	0.0
Total direct plant cost, D	17.73	122.94	17.58	121.86	17.78	123.12	11.63	81.96	11.53	79.88	11.65	80.72
Engineering and contractor's fee, 8% D or 15% D	2.66	9.84	2.64	9.75	2.67	9.85	1.74	12.29	1.73	11.98	1.75	12.11
Project contingency, 15% D	2.66	18.44	2.64	18.28	2.67	18.47	1.74	12.29	1.73	11.98	1.75	12.11
Startup plant modifications, 2% D	0.35	2.46	0.35	2.44	0.36	2.46	0.23	1.64	0.23	1.60	0.23	1.61
Working capital	3.18	29.86	2.83	26.45	2.93	27.39	3.24	30.67	2.88	27.09	2.99	28.19
Land cost[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.30	0.60	0.30	0.60	0.30	0.60
Total capital investment	26.58	183.54	26.04	178.78	26.41	181.29	18.88	139.45	18.40	133.13	18.67	135.34

[a] Land cost for the grassroots facility is included in the offsite facilities cost estimate. Land cost for the battery-limits plant is estimated at $2000 per acre.

Table 4.7. Summary of offsite facilities for the TRW-Meyers fine coal beneficiation plants

---

1. Feed and product coal handling, transporting, and storage facilities.
2. By-product handling and storage facilities.
3. Water procurement, treatment, and pumping facilities.
4. Power and steam generation facilities.
5. Oxygen plant and storage facilities. Order-of-magnitude cost estimates for the oxygen plant and storage facilities were obtained from Linde Division, Union Carbide.
6. Waste treatment handling facilities.
7. Storage and handling facilities for other chemicals required in the process.
8. Office buildings and plant maintenance facilities.
9. Land.
10. Other site improvements such as roads, fences, railroad spurs, etc.

3. Dynamic testing results indicated that the stability of some of the above-mentioned stainless steel alloys was improved when the alloys were subjected to a leaching chemicals environment rich in oxygen. Such an environment would exist, for example, in a simultaneous reactor/regenerator set-up. However, longer-duration dynamic tests need to be conducted before any definitive conclusions can be reached regarding the use of the stainless steel alloys.
4. Armco 22-13-5 (Nitronic-50) austenitic stainless steel was found to be superior to 316 or 316L stainless steels in corrosion resistance and mechanical strength. However, this steel is also more expensive than 316 or 316L stainless steels. The use of the Armco alloy was recommended for stressed parts such as pumps, valves, screens, and wire supports.
5. Acid-resistant concrete can be used to fabricate the pit reactor in the coarse coal processing scheme.
6. Organic inhibitors such as thiourea, dibutyl sulfoxide, etc., used in pickling tanks and proteins such as milk albumin may be helpful in minimizing corrosion problems. However, these should be considered only if they do not adversely affect the leaching process.
7. Teflon and Kynar coatings can also provide additional protection from corrosion in the leaching environment since they are stable in boiling H_2SO_4 and $Fe_2(SO_4)_3$ solutions. Also, since tough, uniform Teflon coatings can be applied on large tubings and inside reaction vessels, these could be considered as strong possibilities in the fabrication of the processing equipment.
8. Further experimental testing still needs to be conducted under actual operating conditions to determine the materials of construction that can be used for the fabrication of the commercial-scale equipment.

The reader is referred to the EPA report[32] for further details regarding the results of the testing of possible materials of construction.

4.1.8 Environmental considerations

The TRW-Meyers process poses no serious threat to the environment. In general, the waste products from the process consist of solid waste materials in the form of iron sulfates and gypsum. These waste materials can be readily disposed of without unduly harming the environment; for example, if the plant is located near the coal mine, the solid waste can be disposed of as landfill in the mine.

Because some of the cleaned coal produced by the process is burned in the plant to provide the plant energy requirements and because the process does not remove the organic sulfur present in the coal, some potential gaseous pollutants such as sulfur oxides and flyash may result. This is especially likely to occur if the process is used to beneficiate coals containing high percentages of both pyritic and organic sulfur. However, the potential air pollutants can be removed by using available flue-gas cleaning technology to meet the applicable EPA emission levels.

4.1.9 Regional consideration

The TRW-Meyers process does not suffer from any regional limitations. However, since the process is especially suited to beneficiating coals having a high percentage of pyritic sulfur, it would be most applicable to coals meeting the above criteria found in the Eastern and Interior Basin coal belts of this country. Also, the process can be located near the coal mine or near the end-use facility.

4.1.10 Conclusions and recommendations

The following conclusions and recommendations can be made regarding the TRW-Meyers coal desulfurization process as a consequence of the present study:

1. The process has been developed based on extensive bench-scale tests conducted on several different kinds of coal. The process is still at the bench-scale stage of development. An 8-ton/day process development unit was expected to be ready by mid-1977 to move the process further toward eventual commercialization.

2. The process is capable of removing up to 95% of the pyritic sulfur from the crushed coal and up to 30% of the ash; in so doing, the heating value of the coal is improved by about 5%.
3. The process is applicable to a wide range of coals, and it poses no serious environmental problem. In fact, it removes a potential environmental pollutant from the coal — namely, sulfur — and transforms it into environmentally innocuous products.
4. The development of the process to a commercial-scale entity may be hastened by supporting the efforts by TRW to complete the tests on their soon-to-be-completed process design unit.

The technical and economic status of the present report can be improved if:

1. more time is available to perform an in-depth study of the process as applied to a particular coal, and
2. an actual commercial-scale plant can be designed and cost-estimated with quotes from equipment vendors instead of using factored costs.

4.2 Battelle Hydrothermal Coal Process[34,35]

4.2.1 Introduction

A chemical beneficiation process developed by Battelle and referred to as the Battelle hydrothermal coal process (BHCP) involves the reaction of an aqueous slurry of -200 mesh coal with sodium hydroxide at an elevated temperature and pressure. Process temperature and pressure conditions reported by Battelle were of a very broad nature — 430 to 650°F for temperature and 350 to 2500 psi for pressure. In this process, the strong caustic reacts with nearly all of the pyritic sulfur, varying amounts of the organic sulfur, some of the coal, and significant quantities of the ash-bearing minerals contained in the coal. The caustic reacts with the sulfur to form a soluble sodium sulfide and is separated from the desulfurized coal by filtration or centrifugation. The desulfurized coal cake retains the major portion of the original mineral matter and about 5% sodium as sodium hydroxide equivalents which impregnated the coal and reacted with the mineral matter during the process. Due to the fineness of the coal, the desulfurized coal cake contains 20 to 30% surface moisture and must be dried. However, in the case of a low-sulfur, low-ash coal requirement, the wet cake is given an acid treatment to dissolve mineral matter, and the clean coal solids are separated by filtration and dried.

Results obtained for a number of coals in laboratory-scale experiments indicate excellent removal of the pyritic sulfur phase and differing degrees of removal of organic sulfur. For the various Eastern and Midwestern bituminous coals examined, data for pyritic sulfur reduction indicate consistently good results in excess of 90% of the total pyritic sulfur present. For the organic sulfur, data reveal somewhat lower and inconsistent extraction results ranging from 24 to 70% for the different coals.

In addition to the sulfur reaction during caustic leaching of the coal, Battelle noted that about 5% of the maf coal is dissolved along with varying amounts of aluminum, silica, and minor metal constituents. After filtration, the spent leachant is sparged with carbon dioxide, converting the sodium sulfide to hydrogen sulfide, precipitating the dissolved coal and ash components, and forming sodium carbonate. Elemental sulfur is recovered from the hydrogen sulfide by treatment in a Claus or similar process. The precipitated coal and ash components are filtered from the sodium carbonate solution and must be processed further to separate the coal value from the ash components. There is no indication that development work has been carried out in this area.

Sodium hydroxide and calcium carbonate are produced by treating the sodium carbonate solution with lime. Again, filtration is used to separate the sodium carbonate from the aqueous caustic solution. After concentration to a 10 to 15% solution of caustic, the recovered sodium hydroxide is recycled to the coal-blending or mixing operation. The calcium carbonate is dried and heated to about 1650°F to make carbon dioxide and lime. The carbon dioxide returns to the sparging system, and the lime recycles to the calcium carbonate precipitation unit.

In addition to markedly lowering the sulfur contents of the coals, Battelle has pointed out several other potentially attractive advantages of coals treated by this process. Of considerable interest is the fact that the Battelle clean-coal process lowered the sulfur levels of coals tested to environmentally acceptable solid fuels for burning in electric-generating facilities or industrial boilers. With respect to sulfur extraction by the BHCP, coals with a high portion of pyritic sulfur will almost always be in the environmentally acceptable category. The chances of coal with high organic sulfur meeting SO_x emission standards when burned are somewhat diminished because the extraction efficiency is generally lower for this sulfur phase, and extraction results have been shown to vary widely from coal to coal. Development efforts should be undertaken to enhance the technology in this area by subjecting a broader spectrum of raw coals to the BHCP.

The process does not produce a low-ash coal; in fact, the ash content may be higher than the original coal, even though a part of the ash is extracted, because of the caustic impregnation. Battelle pointed out that the nondeashed coals, having about 5% sodium hydroxide equivalents, would provide some degree of SO_x emission control by combining with the SO_2 formed during combustion of the coal. If low-ash desulfurized coal is required, the wet desulfurized coal cake can be treated with a dilute acid solution to dissolve the ash components. The type of acid used in the deashing experiments was not revealed, but ash contents of about 1 to 5% were given for the coals examined. Acid consumption is expected to be high in deashing these coals because, in addition to removal of the ash-forming mineral matter, the sodium hydroxide impregnant must be neutralized.

Another advantage of the BHCP extraction step is the tendency to lower agglomeration and swelling characteristics of the coal. The free-swelling index (FSI) is a measure of the agglomeration characteristics of coal. Of the coals treated, the FSI was reduced from 6.0 to 1.0. Coals with agglomerating qualities are usually difficult to use as feedstock in gasification operations without some prior treatment. The BHCP can convert coals that may not be initially useful in gasification operations to suitable feedstocks.

Coals treated by the BHCP have exhibited much higher rates of gasification with hydrogen than the same untreated coals. This is an important benefit because capital and operating costs of coal gasification facilities would be lowered.

Further advantages of the hydrothermal coal cleaning process are: (1) a number of potentially toxic metals are extracted from the coal which might otherwise escape to the atmosphere during combustion; (2) significant amounts of aluminum and silica are extracted and are potentially recoverable; (3) the process can be made essentially a closed-loop system, minimizing the waste-treatment problem; and (4) coal dissolved during hydrothermal treatment is recoverable and might be a good feedstock for organic chemical production.

4.2.2 Detailed process description

A conceptual process block flow diagram has been prepared for the BHCP. Material and energy balances were developed for the three coals in the subset of representative coals. To obtain the capital and operating costs at the recommended plant capacities of 1500 and 15,000 tons/day (maf) of product coal, process designs were prepared for each capacity level for both the grassroots and the battery-limits cases. Only one block flow diagram, Fig. 4.4, is presented since the process information outlined by Battelle was of a very broad nature, many process design assumptions were necessary, and the flow diagrams would differ only in throughput capacity. Quantities shown on the flowsheet are for the Pennsylvania coal. Table 4.8 presents the process assumptions adopted for each coal in developing the process details, block flow diagram, equipment sizing, and capital and operating costs.

In the proposed process, the ROM coal (24 in. x 0) is reduced to 1 in. x 0 in two stages in the primary reduction unit. The sized coal is transferred to a live storage coal yard with a 20-day capacity. From the coal yard, the sized coal is conveyed to the wet pulverization unit where it is reduced to a 70% -200 mesh feedstock. The final size reduction is accomplished in wet ball mills to minimize air pollution problems and to assist in wetting the fine coal. The pulverized coal feedstock is continuously fed to the mixing tanks to which the makeup and recycle caustic leaching agent is introduced. Makeup caustic will be added as a solid and recycle caustic as a 15 to 20% solution. Caustic concentration in the mixers and hydrothermal reactors is 10%. During the mixing period, the coal-caustic slurry is preheated to 150 to 160°F.

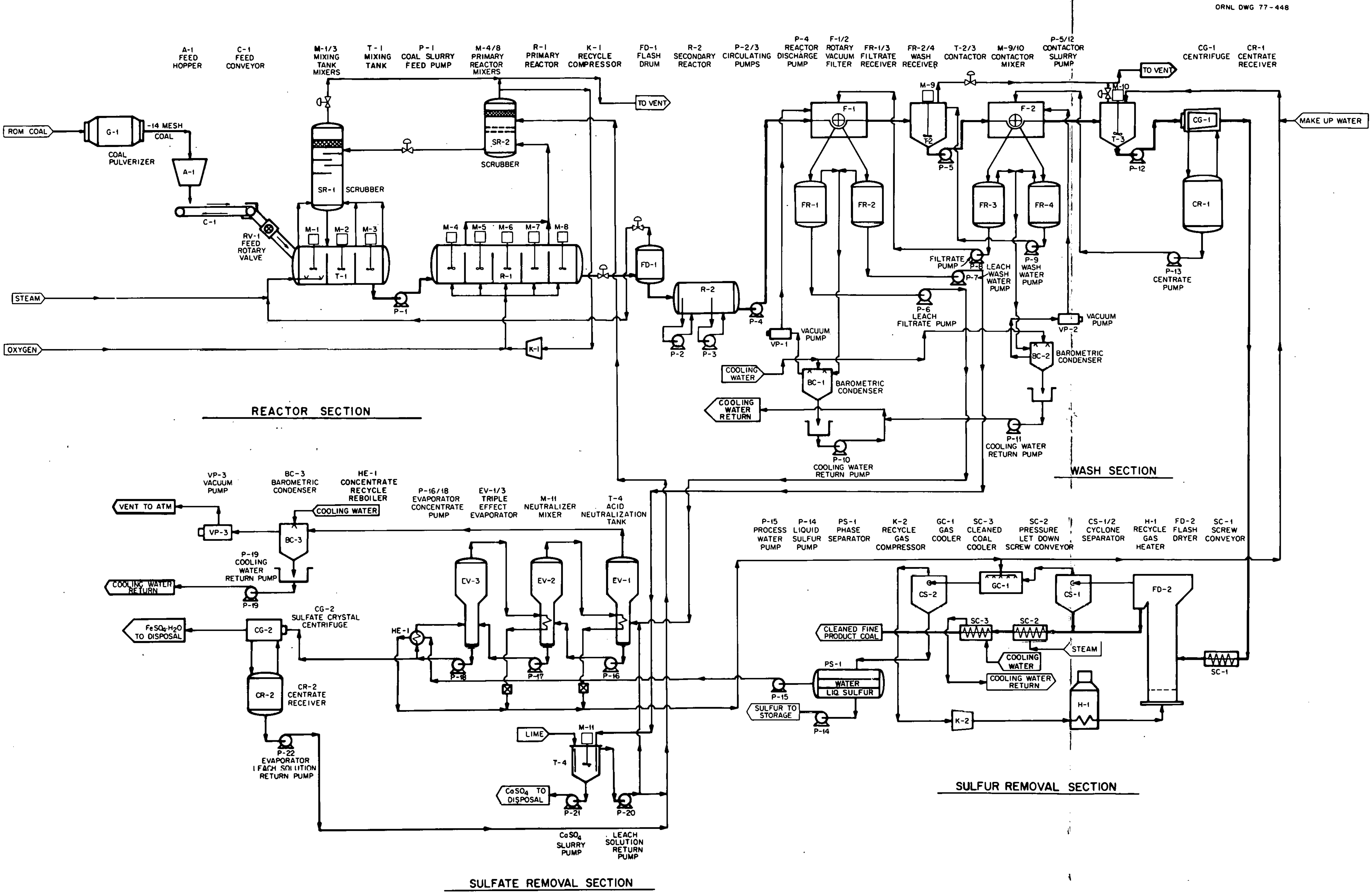


Fig. 4.4. Proposed flow diagram for the Battelle hydrothermal coal process for processing Pennsylvania coal. Nominal plant capacity = 15,000 tons/day of maf product coal.

Table 4.8. Process assumptions for the Battelle hydrothermal coal process evaluation

Process operating conditions:

Continuous process — 24 hr/day, 7 days/week
Coal size — 70% -200 mesh
Process temperature — 475°F
Process pressure — 500 psig
Blending and reaction time — 45 min each
Alkali used for study — sodium hydroxide
Coal irreversibly reacted in the process — 5%
Na (as NaOH equivalents present in
the product coal) — 5%

Impurities removed	Percentage removal		
	Pennsylvania coal	Western Kentucky coal	Illinois coal
Pyritic sulfur[a]	90	94	95
Organic sulfur[a]	24	40	30
Al_2O_3	30	25	20
SiO_2	30	30	30

[a] Based upon similar coals used by Battelle in bench-scale tests.

The blended coal-caustic slurry is pumped to the hydrothermal reactors, which are designed to operate at 475°F and 500 psi. A retention time of 45 min is provided for the sulfur and ash dissolution operation. The reaction products are continuously removed from the autoclaves, cooled, and routed to solid-liquid separators.

Rotary-vacuum disc filters are to be used for the solids-liquid separation because they are probably more reliable than centrifugal-type equipment. The desulfurized coal solids, containing an estimated 15 to 20% moisture, are then dried to a moisture content of 5%. High-pressure, superheated steam from the captive steam plant is used to heat the hydrothermal reactors and to dry the product coal. Steam heating is not the usual method of drying coal but, because the size of this coal is essentially all -200 mesh, steam drying appears to have certain advantages. Most conventional fluid-bed-type dryers are heated with flue gas and normally operate with a large portion of coarse coal and a relatively small amount of fines. They require dust cyclones and wet scrubbers to properly control particulate emission. With all -200 mesh coal, a significant percentage of the dried coal could be expected in the wet scrubber system. Recovery would require the addition of slurry thickeners, filters, and redrying.

The sulfur-bearing effluent from the solids-liquid separation is pumped to a regeneration tower and sparged with carbon dioxide. The reaction generates hydrogen sulfide and sodium carbonate while precipitating aluminum and silicon compounds along with the dissolved coal. The hydrogen sulfide reports to a Claus unit for sulfur recovery. Tail gases from the Claus process are treated in a Beavon and then a Stretford system to reduce H_2S concentration to a level acceptable for discharge to the atmosphere.

The precipitated compounds and precipitated coal are separated by filtration from the sodium carbonate solution. Also included with these solids are a number of the minor metallic ions originally contained in the coal. Because this solid fraction contains about 5% of the original maf coal and a valuable aluminum content, it is necessary that processes be developed for separation and recovery of the valuable constituents.

A dilute sodium hydroxide solution is produced by treating the carbonate solution with lime. The dilute solution is concentrated and recycled to the raw coal mixing unit. Calcium carbonate is also formed in the caustic-forming reaction and is separated by rotary filters. The carbon dioxide and lime used in the process are recovered (and recycled) by indirect heating of the calcium carbonate in rotary kilns.

4.2.3 Equipment and materials of construction

The BHCP is feasible as far as commercially available equipment sizes and materials of construction are concerned. Equipment areas most vulnerable to mechanical failure would be the high-pressure raw coal slurry pumps, the coal dryers, and coal conveying equipment. Failure of this equipment would generally be caused by the abrasive nature of the coal.

Because the process is a caustic system, ordinary steel can be used throughout the low-pressure units with the possible exception of pumps and certain other equipment items that might require abrasion-resistant steels. Low-alloy steel is recommended for the hydrothermal reaction vessels where wall temperatures may reach 500°F at pressures of 500 psia and the steel is potentially subject to caustic embrittlement.

4.2.4 Process evaluation

As mentioned earlier, many assumptions were necessary in preparing the BHCP design. Initially, a complete understanding of the hydrothermal process reaction was necessary before the detailed process design could be attempted. For example: What are the actual coal values dissolved in this operation? How much aluminum and silicon are dissolved, or is an insoluble sodium-aluminum silicate compound formed? What effect does the temperature and pressure parameters have on reaction rates and the amount of coal value dissolved? Also, with respect to sulfur dissolution, pyritic sulfur goes into soluble form very readily, but the organic sulfur dissolution is more difficult and erratic. Therefore, the effects of temperature, pressure, and reaction time exerted on the organic-phase sulfur must be more thoroughly explored.

The hydrothermal sulfur dissolution process is not only the heart of the operation but is, by far, the most costly step in the entire facility. The cost stems from the energy demands required to heat the reactants to the specified operating conditions. It is estimated that about 80% of the steam produced in the steam plant is needed for the hydrothermal process, and this is reflected in the operating and capital costs. Another costly item is the large quantity of sodium hydroxide needed. Even though the greatest portion is recycle material, the fresh makeup amounts to 30 to 40% of the total feed, and all of this loss reports to the product coal as a coal impregnant and/or as a reaction product with the mineral matter. A development effort should be made to determine the best method for recovering the economic value of the caustic contained in the product coal and the associated mineral matter.

One potential method for deashing the coal and recovering the sodium equivalent consists of a sulfuric acid leach to dissolve the ash and form the soluble sodium sulfate. After separating the deashed coal solids, the effluent might be treated with lime to precipitate the mineral matter and sulfate as insoluble calcium salts while leaving the sodium in solution as the hydroxide. Following separation of the caustic solution from the solids, the solution would be concentrated and recycled. Taking into account the different values for the chemicals to be used in the proposed scheme, preliminary estimates indicate that possibly 40 to 50% of the caustic value could be recovered. Even at the 40 to 50% recovery level, a very significant savings would be effected. Two questions come to mind regarding the proposed caustic recovery method: first, can an atmospheric acid treatment react with the sodium if it is impregnated into the coal? and, second, if so, how much of the desulfurized coal would also be dissolved? All of the proposed ideas and questions must be resolved before a reasonable economic assessment can be made.

Once the chemistry of the hydrothermal process is resolved and if no unusual processing difficulties are uncovered, the remainder of the aqueous processing and recovery units should not present technical design problems with the possible exception of the solids precipitated in the regeneration unit. These solids contain about 5 wt % of the maf raw coal, aluminum, silicon, and other metal impurities. Processes need to be developed to separate these components in order to increase the overall process thermal efficiency and to recover the economic values of the materials.

4.2.5 Process water handling

Closed-water loops are used to prevent stream pollution from the BHCP. Evaporation loss and water associated with the product coal are the main process water flows leaving the facility. The principal sources of water evaporation are the coal dryers, drying of calcium carbonate before calcining, and the recycle sodium hydroxide concentration unit.

In a case where deashing of the product coal would be needed, equipment is required for neutralizing the spent acid leachant. Lime (with flocculating and coagulating agents) would be a logical choice if sulfuric acid is the leachant because of the insolubility of the resultant calcium sulfate and hydroxides. This residue would not present an environmental problem. Water would be recycled after separation from the precipitated solids.

4.2.6 Air quality control

The major sources of potential air pollution from the BHCP are the coal drying and combustion of the product coal in the steam plant and lime kilns. The coal-drying operation will be designed with wet scrubbers for controlling the coal dust entrained with the water vapor. The coal fines will be recovered and recycled.

All coals processed by the BHCP will not have sufficiently low sulfur contents to meet the EPA sulfur oxide emission standards when burned. Therefore, for those cases the steam plant must be equipped with a flue-gas desulfurization system. Flue gases from the lime kilns would also report to the scrubber for treatment. The fixed calcium sulfate would be combined with the other solid refuse generated in the plant.

4.2.7 Solid wastes

Solid wastes generated in a BHCP would be reject rock from primary crushing, ash from the steam plant, lime recovery, and fixed calcium sulfate from flue-gas desulfurization (if needed). When deashed coal is called for, additional waste material will be produced in the effluent treatment system. Estimates show that the deashed coal residue would be about equal to the combined rock and ash waste while the refuse from desulfurization would amount to about 1 wt %. The combined waste stream would be trucked or conveyed to the mine for disposal.

The rock and ash wastes are highly resistant to leaching and should pose no problems in mine sites. The deashed coal residue and flue-gas desulfurization waste are basically hydroxides and calcium sulfate and, when combined with the rock and ash refuse, should not pose any threat to the environment.

4.2.8 Economic analysis

The results obtained by the BHCP for the beneficiation of the Pennsylvania, western Kentucky, and Illinois coals are summarized in Tables 4.9 and 4.10 for the grassroots and the battery-limits types of facilities. For this evaluation, the coals were assumed to be desulfurized but not deashed as indicated by the high ash content of the clean product coal. Referring to Tables 4.9 and 4.10, it should be noted that the material and thermal recoveries for the grassroots plants are quite low when compared to similar recoveries for the battery-limits plants. The reason for the low recoveries is that, in the case of the grassroots plants, additional raw coal is required to generate the steam and power requirements of the process, whereas these requirements are assumed to be purchased in the case of the battery-limits plants. Also, 5% of the coal heating value is associated with the aluminum and silica stream that may be recoverable but is not included in the above figures.

Detailed economic analyses were performed for the 1500- and 15,000-ton/day conceptual plants based on the BHCP. The analyses were performed for both the grassroots and the battery-limits cases. Details of the operating cost, working capital, and projected capital investment are presented in Tables 4.11, 4.12, and 4.13 respectively. In addition, a summary of the above costs for the conceptual BHCP plants is given in Table 4.14, together with selected, representative values of the cleaned product coal price. The results of the economic analyses on the BHCP are presented graphically for the 12 and 15% AARR cases in Appendix B. The calculated cleaned product coal prices were determined by using ORNL-developed computer program PRP for ROM coal costs ranging

Table 4.9. Summary of the results for the beneficiation of the coals by the BHCP process

Facility type: grassroots

	1500-ton/day facility						15,000-ton/day facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	4404	3201	3156	2677	3539	2893	44,035	32,013	31,555	25,767	35,389	28,931
Ash, %	27.3		15.2		18.25		27.3		15.2		18.25	
Total sulfur, %	2.90		2.55		4.21		2.90		2.55		4.21	
Total moisture, % (assumed)	10.0		10.0		10.0		10.0		10.0		10.0	
HHV, Btu/lb		15,194		14,357		13,877		15,194		14,367		13,877
B. Clean coal product	2177	1500	1905	1500	1984	1500	21,796	15,000	19,050	15,000	19,836	15,000
Ash, %	31.8		21.3		24.38		31.8		21.3		24.38	
Total sulfur, %	0.6		0.62		1.28		0.6		0.62		1.28	
Total moisture, % (premised)	5.0		5.0		5.0		5.0		5.0		5.0	
HHV, Btu/lb		14,348		13,575		13,196		14,348		13,575		13,196
Potential thermal energy, 10^9 Btu/day												
Raw coal feed		97.28		76.91		80.30		972.8		769.1		803.0
Clean coal product		43.04		40.73		39.59		430.0		407.0		396.0
Sulfur		0.81		0.49		0.83		8.14		4.85		8.29
Percent recovery												
Material[a,e]	49.5		60.4		56.1		49.5		60.4		55.1	
Thermal[b]		45.1		53.6		50.3		45.0		53.6		50.4
Beneficiation cost[c,d]												
$ per ton[f]	59.51		50.60		50.43		47.19		40.09		42.18	
¢ per million Btu[g]		3.12		2.46		2.75		2.47		1.95		2.18

---

[a] Material recovery = $\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}} \times 100$.

[b] Thermal recovery = $\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}} \times 100$.

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

[e] Includes additional ash due to impregnation of leachant in coal.

[f] For moist product coal.

[g] Based on the heating value of moist, cleaned product coal.

Table 4.10. Summary of the results for the beneficiation of the coals by the BHCP process

Facility type: battery limits

	1500-ton/day facility						15,000-ton/day facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf	mf	maf
Daily flow, tons/day												
A. Raw coal feed	2242	1630	1905	1616	2002	1637	22,424	16,302	19,054	16,158	20,020	16,366
Ash, %	27.3		15.2		18.25		27.3		15.2		18.25	
Total sulfur, %	2.90		2.55		4.21		2.90		2.55		4.21	
Total moisture, % (assumed)	10.0		10.0		10.0		10.0		10.0		10.0	
HHV, Btu/lb		15,194		14,367		13,877	1	15,194		14,367		13,877
B. Clean coal product	2177	1500	1905	1500	1984	1500	21,796	15,000	19,050	15,000	19,836	15,000
Ash, %	31.8		21.3		24.38		31.8		21.3		24.38	
Total sulfur, %	0.6		0.62		1.28		0.6		0.62		1.28	
Total moisture, % (premised)	5.0		5.0		5.0		5.0		5.0		5.0	
HHV, Btu/lb		14,348		13,575		13,196		14,348		13,575		13,196
Potential thermal energy, 10^9 Btu/day												
Raw coal feed		49.54		46.43		45.42		495.4		464.3		454.2
Clean coal product		43.04		40.73		39.59		430.0		407.0		396.0
Sulfur		2.93		2.68		0.79		29.74		27.12		7.78
Percent recovery												
Material[a,e]	97.2		100.0		99.1		97.2		100.0		99.1	
Thermal[b]		92.8		93.5		88.9		92.8		93.5		88.9
Beneficiation cost[c,d]												
$ per ton[f]	62.09		55.74		56.55		63.37		52.33		56.46	
¢ per million Btu		3.25		2.71		2.92		3.32		2.55		2.92

[a] Material recovery = $\frac{\text{weight of cleaned product coal}}{\text{weight of raw feed coal}} \times 100.$

[b] Thermal recovery = $\frac{\text{heating value of cleaned product coal}}{\text{heating value of raw feed coal}} \times 100.$

[c] Beneficiation cost is the cost involved in cleaning (beneficiating) the raw coal. It does not include the cost of the ROM coal required to produce the cleaned product coal.

[d] Costs reported are calculated based on $20 per ton ROM coal cost, 70:30 debt/equity ratio for plant capital, 12% annual after-tax rate of return on equity capital, and 9% annual interest rate on debt.

[e] Includes additional ash due to impregnation of leachant in coal.

[f] For moist product coal.

[g] Based on the heating value of moist, cleaned product coal.

Table 4.11. BHCP - operating cost summary

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Utilities[a]												
Electric power at 2.5¢/kWhr	0.0	0.0	0.0	0.0	0.0	0.0	1.673	12.440	1.673	12.440	1.673	11.990
Steam at $1.90/1000 lb	0.0	0.0	0.0	0.0	0.0	0.0	5.617	171.566	3.933	120.270	4.827	147.419
Chemicals[a] (including water)	29.340	293.364	21.307	213.071	23.922	239.221	26.429	264.321	19.177	191.957	21.450	214.522
Operating labor cost												
Process operating labor	0.772	1.728	0.581	1.526	0.711	1.593	0.604	1.258	0.554	1.191	0.570	1.191
Supervisory personnel cost	0.154	0.346	0.136	0.305	0.142	0.319	0.121	0.252	0.111	0.238	0.114	0.238
Labor burden	0.324	0.726	0.286	0.641	0.299	0.669	0.254	0.528	0.238	0.500	0.239	0.500
Plant maintenance cost (including maintenance materials, labor, supervision, and maintenance labor burden)	2.419	12.124	1.389	9.469	2.100	10.525	2.163	6.669	1.666	4.173	1.873	5.082
Operating supplies[a]	0.232	0.518	0.204	0.458	0.213	0.478	0.181	0.377	0.166	0.357	0.171	0.357
General administrative overhead cost	1.431	5.886	1.164	4.704	1.267	5.166	1.179	3.171	0.954	2.289	1.046	2.652
Waste disposal cost[a]	0.840	3.392	0.452	4.522	0.561	5.606	0.328	3.587	1.771	2.582	0.220	2.907
Property insurance cost	0.493	2.423	0.385	1.894	0.428	2.105	0.441	1.360	0.340	0.851	0.382	1.037
Total gross operating cost[b]	36.005	325.507	26.504	236.590	29.643	265.682	38.990	465.529	30.583	336.848	32.565	387.895
By-product credit	1.998	19.975	1.193	11.925	2.032	20.320	1.017	10.173	0.720	7.199	1.513	15.130
Total net operating cost[b,c]	34.007	305.532	25.311	224.665	27.611	245.362	37.973	455.356	29.863	329.649	31.052	372.765

[a] The costs shown are reported for a 100% plant service factor. For other plant service factors, multiply the cost for the items marked with an "a" by the desired service factor to obtain the appropriate annual operating cost.

[b] The costs shown do not include the feedstock cost, depreciation, and taxes. These costs are accounted for separately as a part of the analyses in the computer program FRP.

[c] Further details regarding the costs are presented in Appendix A.

Table 4.12. BHCP - working capital summary

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Raw coal inventory at $20 per ton (20 days)	1.761	17.614	1.263	12.626	1.416	14.156	0.897	8.970	0.762	7.622	0.801	8.008
Product coal inventory at $30 per ton (30 days)	1.962	19.616	1.715	17.145	1.785	17.852	1.962	19.616	1.715	17.145	1.785	17.852
Gross operating costs	3.009	25.754	2.178	19.446	2.269	21.837	3.205	38.263	2.514	27.686	2.677	31.882
Total working capital	6.732	63.984	5.156	49.217	5.470	53.845	6.064	66.849	4.991	52.453	5.263	57.742

Table 4.13. BHCP - capital investment summary

Plant size, in tons/day of maf product coal
All values are in millions of dollars.

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Direct plant cost, D	48.38	242.48	37.79	189.38	42.00	210.50	43.25	133.38	33.32	83.47	37.46	101.65
Engineering and contractor's fee, 8% D or 15% D	7.26	19.40	5.67	15.15	6.30	16.84	6.49	10.67	5.00	12.52	5.62	8.13
Project contingency, 15% D	7.26	36.37	5.67	28.41	6.30	31.58	6.49	20.01	5.00	12.52	5.62	15.25
Start-up plant modifications, 2% D	0.97	4.85	0.76	3.79	0.84	4.21	0.87	2.67	0.67	1.67	0.75	2.03
Working capital	6.73	63.98	5.16	49.22	5.47	53.84	6.06	65.35	4.99	52.45	5.26	57.54
Land cost at $2000 per acre	0.80	1.20	0.80	1.20	0.80	1.20	0.80	1.20	0.80	1.20	0.80	1.20
Total capital investment	71.40	368.28	55.85	287.15	61.71	318.17	63.96	234.78	49.78	163.83	55.51	186.00

Table 4.14. Economic analyses summary for the conceptual BHCP beneficiation plants[a]

Plant size, in tons/day of maf product coal

Cost component	Grassroots facility						Battery-limits facility					
	Pennsylvania coal		W. Kentucky coal		Illinois coal		Pennsylvania coal		W. Kentucky coal		Illinois coal	
	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000	1500	15,000
Cost, $$10^5$												
Direct capital	48.38	242.48	37.79	189.38	42.00	210.50	43.25	133.38	33.32	83.47	37.46	101.65
Annual operating (gross)[b]	32.76	295.28	24.31	214.79	27.17	241.15	35.57	420.30	27.91	304.09	29.73	350.18
Working capital	6.73	63.98	5.16	49.22	5.47	53.84	6.06	66.85	4.99	52.45	5.26	15.25
Total capital investment	71.40	368.28	55.85	287.15	61.71	318.17	63.96	234.78	49.78	163.83	55.51	186.00
Product coal price, $ per ton[c]												
At 12% AARR[d]	99.91	87.59	83.74	73.23	89.11	77.86	82.67	83.95	75.74	72.33	76.74	76.65
At 15% AARR	101.42	88.49	85.09	74.02	90.54	78.70	84.04	84.56	76.95	72.82	78.03	77.19

---

[a] The beneficiation plants were designed to operate 3 shifts/day, 7 days/week with 90% annual plant service factor.

[b] For 90% plant service factor.

[c] Calculated product coal price based on $20 per ton ROM coal, 70:30 debt/equity ratio, and 9% annual interest rate on debt fraction of capital. This value includes the ROM coal cost.

[d] AARR = annual after-tax rate of return on equity capital.

between \$10 per ton and \$50 per ton and for debt/equity ratios of 0:100, 30:70, 70:30, and 95:5.

Referring to Table 4.9, the beneficiation costs for the Pennsylvania coal, for example, by the BHCP are calculated to be \$59.51 and \$47.19 per ton of mf raw coal for the 1500- and 15,000-ton/day capacity grassroots beneficiation facilities. Similar costs were calculated for the other coals examined. The process appears to be a relatively costly process for beneficiating coal. It should be noted that the beneficiation cost developed reflects only the desulfurization, separation, and drying costs. If a desulfurized-deashed coal is to be produced, the beneficiation costs will be significantly higher.

The by-product credit indicated in Table 4.11 is the credit for the sulfur produced. It is recognized that some aluminum, silica, and about 5 wt % of the maf coal could be considered by-products. However, it was felt that these latter product values should be excluded from the by-product credit until a feasible separation scheme is developed and the relative separation costs are determined.

4.2.9 Application to the other coals tabulated in Table 1.2

The two coals listed in Table 1.2 that will not meet the EPA SO_x emission standards (1.2 lb of SO_2 per million Btu) when burned and not previously discussed under the BHCP chemical beneficiation section are from Rock Springs No. 11 bed (Sweetwater County, Wyoming), a subbituminous coal, and from Dakota Star Mine (Mercer County, North Dakota), a lignite coal. Each of these coals has a low total sulfur and with only a small reduction in sulfur content will comply with SO_x emission regulations. Assuming that the subbituminous and lignite coals respond in a manner similar to eastern bituminous coals subjected to the BHCP, it is postulated that, at a minimum operating temperature (430°F), the BHCP caustic leaching will remove 80 to 90% of the pyrite present in these coals, which is actually more than necessary for the coals to meet stack gas SO_x emission standards of 1.2 lb of SO_2 per million Btu. At the minimum processing conditions, the organic sulfur should not react. Even with the sulfur reduction potential offered by the BHCP on western subbituminous and lignite coals, an economic analysis would indicate even higher beneficiation costs than determined for the eastern bituminous coals. Drying costs will be higher for these coals because of the greater quantities of bed moisture to be removed. Also, because of the moisture content of the coal, larger tonnages of ROM subbituminous and lignite coals are needed than for low-moisture bituminous coals to produce an equivalent product tonnage. Primary size reduction and pulverizing costs will be affected by this increase.

A factor that may prove to be very serious when subbituminous and lignite coals are processed by the BHCP is drying the fine-size coal (70% -200 mesh) coupled with the pyrophoric nature of such coals.

In summary, the BHCP method for chemical beneficiation of the western subbituminous and lignite coals will produce sufficiently low-sulfur product coals that comply with EPA SO_x emission standards but at high costs. The production costs would probably be more than the cost of flue-gas desulfurization if these low-rank--low-sulfur coals were consumed without beneficiation. Moreover, the desulfurized product coal would contain large amounts of caustic, be of a lower heating value, and have a higher ash content. In addition, unless a deashing step augmented the beneficiation process, subsequent transportation costs would be higher than for dried untreated coal. The application of the BHCP chemical beneficiation method to low-sulfur western coals does not appear to offer economic justification or sufficient product coal improvements to warrant any more than an exploratory research effort to resolve the predictions made in this section.

4.3 Sodium Hydroxide Beneficiation Method Developed by U.S. Bureau of Mines at the Pittsburgh Energy Research Center

4.3.1 General process description

The bench-scale chemical beneficiation process[36,37] worked out by the Pittsburgh Energy Research Center (PERC) removes nearly all of the pyritic sulfur content of the coal. In this process, a coal-water slurry of coal is heated to 440°F for 2 hr in an autoclave containing sodium hydroxide (10% NaOH). The caustic treatment converts nearly all of the pyritic sulfur to the soluble sodium sulfide, no organic sulfur is extracted, nor are the caking qualities of the coal altered. A subsequent, dilute acid leaching operation is required to dissolve the ash components to produce a low-ash, low-pyrite coal. At this processing temperature, a fuel value loss of about 10% was reported.

By increasing the processing temperature to 572°F, about 30 to 40% of the organic sulfur is extracted. The caking qualities of the coals are destroyed at the higher treatment temperature, and it was reported that the coal fuel value losses were much higher for the more rigorous treatment.

4.3.2 Comparison with Battelle hydrothermal coal beneficiation process

The PERC coal beneficiation process is very much like the Battelle hydrothermal coal process. Comparison of the beneficiation data of both processes revealed that almost identical results were obtained. Each process removed 90 to 98% of the pyritic sulfur and varying amounts up to 70% of organic sulfur. A dilute acid leaching step was needed to deash the coal, and if the caking characteristics of the coal were to be destroyed, higher operating temperatures were required.

The coals tested by PERC contained a high organic sulfur content, and the resultant beneficiated coals, if combusted, would not meet present-day EPA standards for SO_x emission in the flue gas. In the Battelle coal desulfurization investigations, primarily low-organic-sulfur-content coals were used, and, as could be expected, essentially all of their cleaned coals would meet EPA SO_x standards if burned.

A somewhat significant variation was observed in the coal fuel values reported for the two processes. Battelle reported losses of about 5%, whereas PERC indicated losses of 10% at 440°F and much greater losses at the higher operating temperatures. In considering the difference in loss, it is possible that Battelle may have been assuming, in their material accountability, a coal fuel value credit for the potentially recoverable coal in the spent leach solution. Because of the similarity of the PERC process with the Battelle hydrothermal coal process, the technical and economic evaluations presented for the latter process would also apply to the PERC beneficiation process.

Results of applying the caustic process investigated by the U.S. Bureau of Mines (PERC) to beneficiation of the western-type subbituminous and lignite coals would be the same as those for the BHCP because the two beneficiation processes are essentially identical.

4.4 SURC Chemical Comminution Process

4.4.1 Introduction

Syracuse University Research Center (SURC) has developed a coal beneficiation process in which the raw coal is reduced in size by chemical agents rather than by mechanical crushing methods. The process is known as the chemical comminution process. In reducing the size of the raw coal, the mineral matter (which contains the ash and the pyritic sulfur constituents) in the coal is liberated. Only the ash and the pyritic sulfur are liberated from the coal in this process because the chemicals used do not react to a significant extent with the coal matrix. Hence, the process does not reduce the organic sulfur level of the coal. The mineral matter liberated from the coal by the chemical agent is then separated from the coal by using conventional coal washing methods such as the float-sink technique.

The SURC chemical comminution process essentially consists of treating the raw coal with a suitable chemical agent (for example, anhydrous liquid ammonia) at ambient temperatures and pressures for a period of about 1 hr. The chemical agent induces selective breakage of the coal along already existing boundaries that contain the mineral matter. The chemically comminuted coal is then subjected to a conventional float-sink type operation wherein the coal is separated from the liberated pyritic sulfur and the ash. Some of the chemicals that have been tested as comminuting agents are methanol, anhydrous liquid and gaseous ammonia, n-propylamine, and pyridine. Of these chemicals, ammonia and methanol were determined to be the most effective comminuting agents. Also, the tests revealed that the degree of chemical comminution achieved appears to decrease as the coal rank increases.[38]

The developers of the process claim[38,39] that the combined chemical comminution (using anhydrous liquid ammonia) and float-sink process has the following advantages:

1. The process can reduce the pyritic sulfur of the bituminous coal by about 73% and the ash content by about 55%.
2. The process produces less fine coal. Approximately 90% of the product coal from the process is +32 mesh (+495 μm). This indicates a significant reduction in the amount of fine coal produced and, hence, an attendant reduction in the cost of handling the coal product.
3. The process produces a better beneficiated coal product than mechanical grinding to the same particle size combined with a float-sink type cleaning operation.
4. The processing costs are further reduced since the process uses commonly available chemical agents. Also, 99+% of the chemical agent used can be readily recovered and reused.
5. The cost of producing clean coal by the process has been estimated by the process developers to be around \$2.50 to \$3.00 per ton of product coal. This compares very favorably with the cost of alternate processes for producing clean coal.

The process is still in the early stages of development. Most of the development work on the process has been conducted in bench-scale equipment capable of processing around 20 lb/hr (~9.1 kg/hr) of coal. The development effort on the process is continuing with eventual commercialization of the process in mind.

Much more detailed evaluation of the process must still be completed before the process reaches the commercialization stage. However, the process appears to present an economical means of reducing the sulfur and ash contents of several Eastern Basin coals.

4.4.2 Process description

Figure 4.5 is a block flow diagram of the conceptual commercial-scale embodiment of the SURC chemical comminution process. The block flow diagram was developed based on information obtained from ref. 39. Referring to Fig. 4.5, 3 in. x 0 (76 mm x 0) size consist ROM coal is visualized as feed to the beneficiation plant. The feed coal is screened and mechanically crushed so that the size consist of the feed to the comminuting reactor is reduced to 1-1/2 in. x 0 (38 mm x 0). The mineral matter that is liberated from the ROM coal in the course of the mechanical grinding and screening operations is separated and disposed of appropriately. The 1-1/2 in. x 0 (38 mm x 0) size coal then enters the comminuting reactor (shown as the ammonia reactor in Fig. 4.5) where it is intimately mixed with a comminuting agent such as anhydrous liquid ammonia. The chemical comminution process is allowed to occur for up to 2 hr. Following the comminution step, the coal is washed free of the comminuting agent and is then sent to a conventional coal separation step such as heavy-medium separation where the liberated pyritic sulfur and ash are removed from the coal mass. The cleaned coal is then dewatered and prepared for shipment to the end-use facility.

The ammonia that is separated from the coal in the ammonia washing step is distilled, compressed, and liquefied for reuse. A small fraction of the cleaned product coal is used in the plant to meet the process energy requirements.

4.5 Ledgemont Oxygen Leaching Process

4.5.1 Introduction

The Ledgemont oxygen leaching (LOL) process is a chemical coal beneficiation process developed by the Ledgemont Laboratory of Kennecott Copper Corporation. In the LOL process the pulverized coal (-100 mesh)

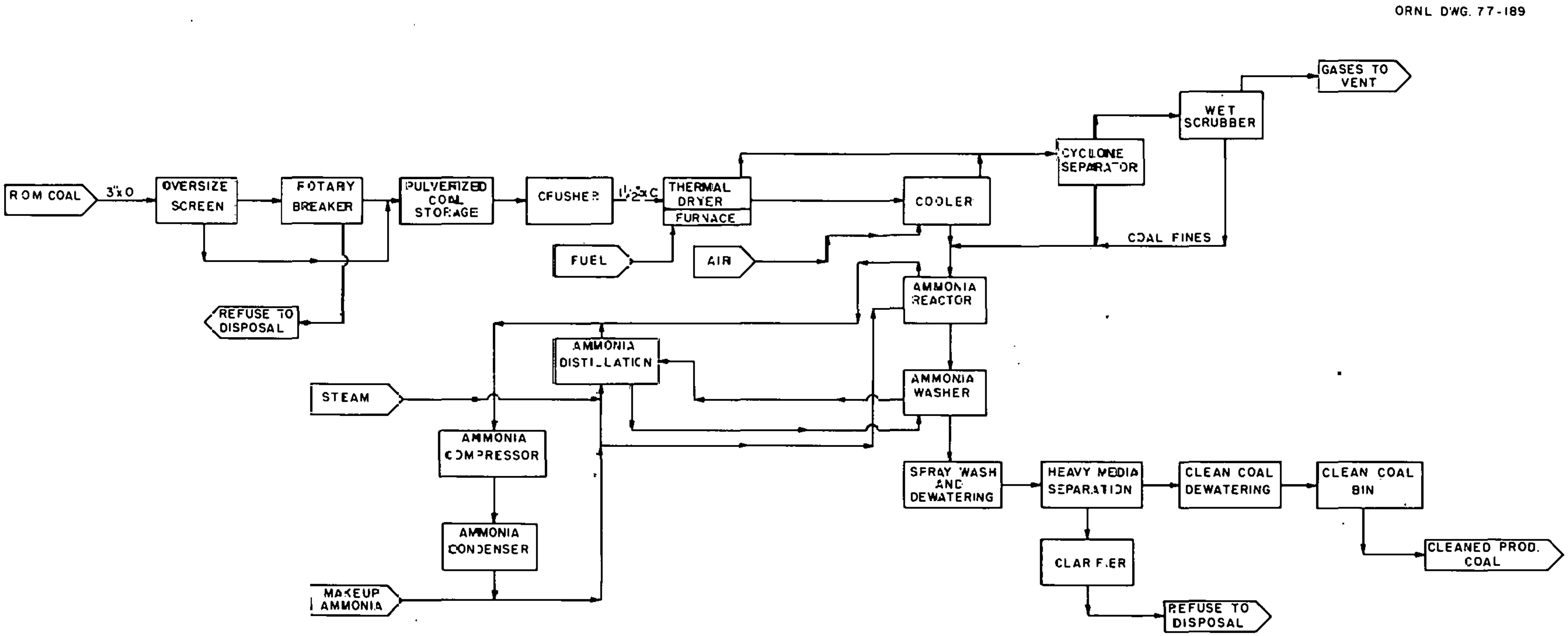


Fig. 4.5. Block flow diagram for the SURC chemical comminution process.

is slurried with water and reacted with high-purity oxygen at temperatures ranging between 212 and 266°F (100 and 130°C) and at pressures up to 300 psi (~2.2 MPa) for approximately 2 hr. The chemistry of the reaction may be represented by the following equation:[40]

$$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \ . \qquad (4)$$

The process conditions are regulated so that no free sulfur is formed in the process. This obviates the necessity for the relatively difficult and expensive sulfur recovery step required in the TRW-Meyers process, for example. Following the reaction, the coal mass is separated from the soluble impurities and is washed and dried to yield the cleaned product coal.

The developers of the process claim that it is capable of removing more than 90% of the pyritic sulfur present in the coal. However, the process does not generally remove the organic sulfur present in the coal. In addition, the following claims are made for the process:[41]

1. Unlike the TRW-Meyers process, the LOL process requires no regeneration of the leach solution. However, the spent leach solution does have to be neutralized and filtered before it can be reused.
2. The reaction time for the depyritization of the coal (about 2 hr) is much less than that required for the TRW-Meyers process.
3. Fewer wash steps are required to clean the coal following the depyritization reaction than required for the TRW-Meyers process.
4. No elemental sulfur recovery steps are required.
5. The process is cost competitive with stack gas scrubbing for reducing the sulfur emissions from coals having low organic sulfur content.

A newer version of the LOL process known as the ammonia-oxygen-water (AOW) process was reported on recently by Sareen.[42] The following information regarding the AOW process was developed from the above paper:

1. In this process, the pulverized coal (-100 mesh) is treated with oxygen in an ammoniacal solution instead of just water, at

approximately the same reaction conditions as indicated above for the LOL process. The chemistry of the depyritization reaction may be given by the following equation:

$$FeS_2 + 4NH_3 + 3.5H_2O + 3.75O_2 \rightarrow 4NH_4^{+} + 2SO_4^{2-} + Fe(OH)_3 \ . \qquad (5)$$

2. The AOW process is claimed to be able to remove not only more than 90% of the pyritic sulfur present in the coal but also to remove up to 25% of the organic sulfur present in the coal.
3. An 8 to 13% Btu loss from the coal occurs when the coal is treated by the AOW process. This coal loss is attributed to the formation of coal acids.

Process development has been conducted to date in batch-type bench-scale equipment with funding provided by Kennecott Copper Corporation. A detailed engineering evaluation of a commercial-scale plant based on the LOL process has been conducted in-house by Ledgemont Laboratory. However, the engineering evaluation report is proprietary to Kennecott Copper Corporation.[43] Further development of the process, beyond the bench-scale level, appears to be dependent upon the resolution of the Peabody Coal Company divestiture case pending against Kennecott Copper Corporation.[43]

4.5.2 Process description

Figure 4.6 is a block flow diagram of the conceptual commercial-scale embodiment of the LOL process. Referring to Fig. 4.6, ROM coal is normally crushed to -1/8-in. (~3.2-mm) size and is physically cleaned (generally by water washing) to remove the rock and clay materials that may accompany it before being fed to the process. The crushed, physically cleaned coal is then pulverized to -100-mesh size and is slurried with water. The coal-water slurry is fed to the leaching reactors where it is reacted with high-purity oxygen at temperatures of 212 to 266°F (100 to 130°C) and at pressures up to 300 psi (~2.2 MPa) for approximately 2 hr. The pyritic sulfur in the coal reacts with the pure oxygen and is converted into soluble sulfates and sulfuric acid according to the reaction given by Eq. (4). As indicated earlier, the reaction conditions are maintained such that no free sulfur is formed in the process.

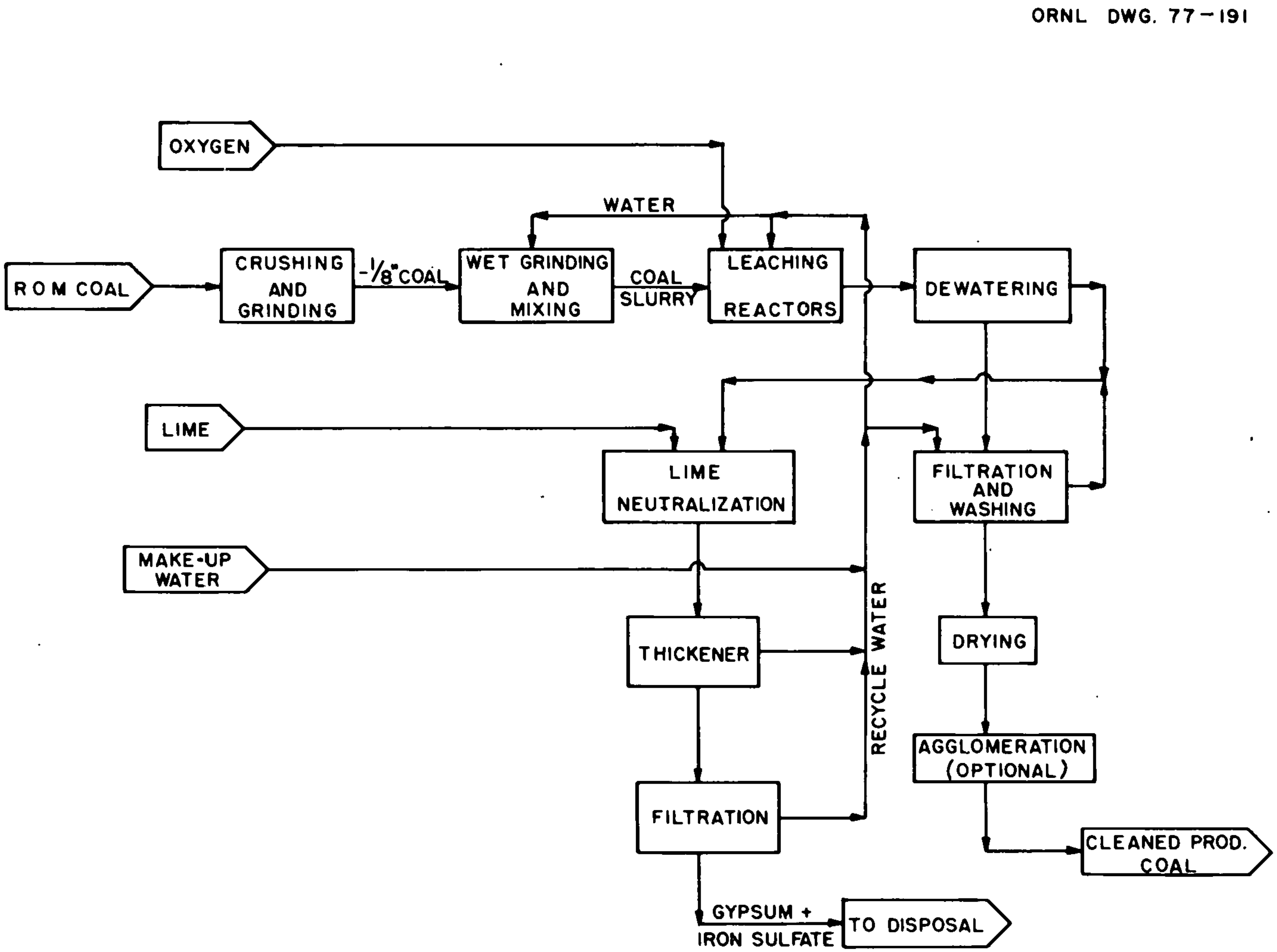


Fig. 4.6. Block flow diagram for the Ledgemont oxygen leaching process.

The depyritized coal mass from the reactors is then separated from the soluble sulfates and is washed with hot water to remove the residual sulfates present in the coal. Following the filtration and washing steps, the cleaned coal is dried and prepared for shipment to an end-use facility such as a power plant. Preparation of the clean product coal may consist of agglomerating the coal with a suitable binder to make it more amenable to being shipped.

The sulfate solutions from the filtration and washing steps are combined and neutralized by the addition of lime and are then filtered. The filter cake, consisting mainly of iron and aluminum sulfates and gypsum, is sent to the waste disposal pit while the filtrate, which is mainly water, is reused at the head end of the process.

4.6 KVB Coal Desulfurization Process

4.6.1 Introduction

KVB Engineering, Inc., obtained a patent[44] in September 1975 for a coal desulfurization process. This process will hereafter be referred to as the KVB coal desulfurization process or, more simply, as the KVB process. In the KVB process the coal is claimed to be desulfurized by the action of gaseous NO_2 (in the presence of oxygen and nitrogen), which selectively oxidizes the organic and inorganic sulfur in the coal. The sulfur oxides formed are then separated from the coal by conventional means to yield a desulfurized coal product.

The following description of the process has been developed from the above-mentioned patent. The process consists of treating the pulverized raw coal [generally, +28 mesh (589 µm) in size] with a mixture of four gases for 1 to 30 min at pressures between 1 and 20 atm (0.1 and 2 MPa) and temperatures between 100 and 500°F (38 and 260°C). The composition of the reacting gas is reported to be as follows: O_2 (0.5 to 20 vol %), NO (0.25 to 10 vol %), NO_2 (0.25 to 10 vol %), and N_2 (the remainder). The sulfur present in the coal is removed as gaseous sulfur oxides or soluble sulfates. The reaction conditions are maintained such that no free sulfur is formed during the reaction. The gaseous sulfur oxides are removed in the reactor while the soluble sulfates are removed by subsequent water and caustic washing of the coal. Washing the coal also reduces its ash content. The washed coal is then dried to yield the cleaned product coal. Other effluents from the process are either recycled in the process or are disposed of as wastes or by-products of the process.

KVB claims that the process can remove all three forms of sulfur present in coal — namely, pyritic, organic, and sulfate sulfur. They also claim that, under certain test conditions, sulfur removal of up to 90% was obtained.[45]

KVB Engineering, Inc., has funded the total development of the process up to this point, and the process technology is proprietary to KVB. They are seeking funding for further development of the process. Most of the development work up to now has been on a small bench-scale level. Further development of the process is envisaged to consist of testing the process in a larger laboratory-scale unit followed by testing in a 10-ton/day coal pilot plant to establish the commercial feasibility of the process.

The process is very similar to the other chemical desulfurization processes discussed in this report, notably the Battelle hydrothermal and the PERC processes, with the exception that NO_2 is used as an added step to aid in the desulfurization of the coal.

4.6.2 Process description

A block diagram of the KVB process using a continuous reactor is given in Fig. 4.7. The figure was developed from ref. 45. A batch reactor can be used instead of the continuous reactor. If a batch reactor is used, the reaction and the extraction steps can be performed in the same vessel. Data are not available at this time to determine which of the two modes would be more economical.

Referring to Fig. 4.7, the raw coal is fed into the pulverizer where it is generally crushed to a -14 +28 mesh size consist. However, the process is claimed to be capable of desulfurizing coals ranging from 1/4-in. (~6-mm) to 200-mesh size. The pulverized coal is fed into the reactor where it is reacted with the mixture of four gases (namely, O_2, NO, NO_2, and N_2) for 1 to 30 min at a pressure between 1 and 20 atm

ORNL DWG. 77-653

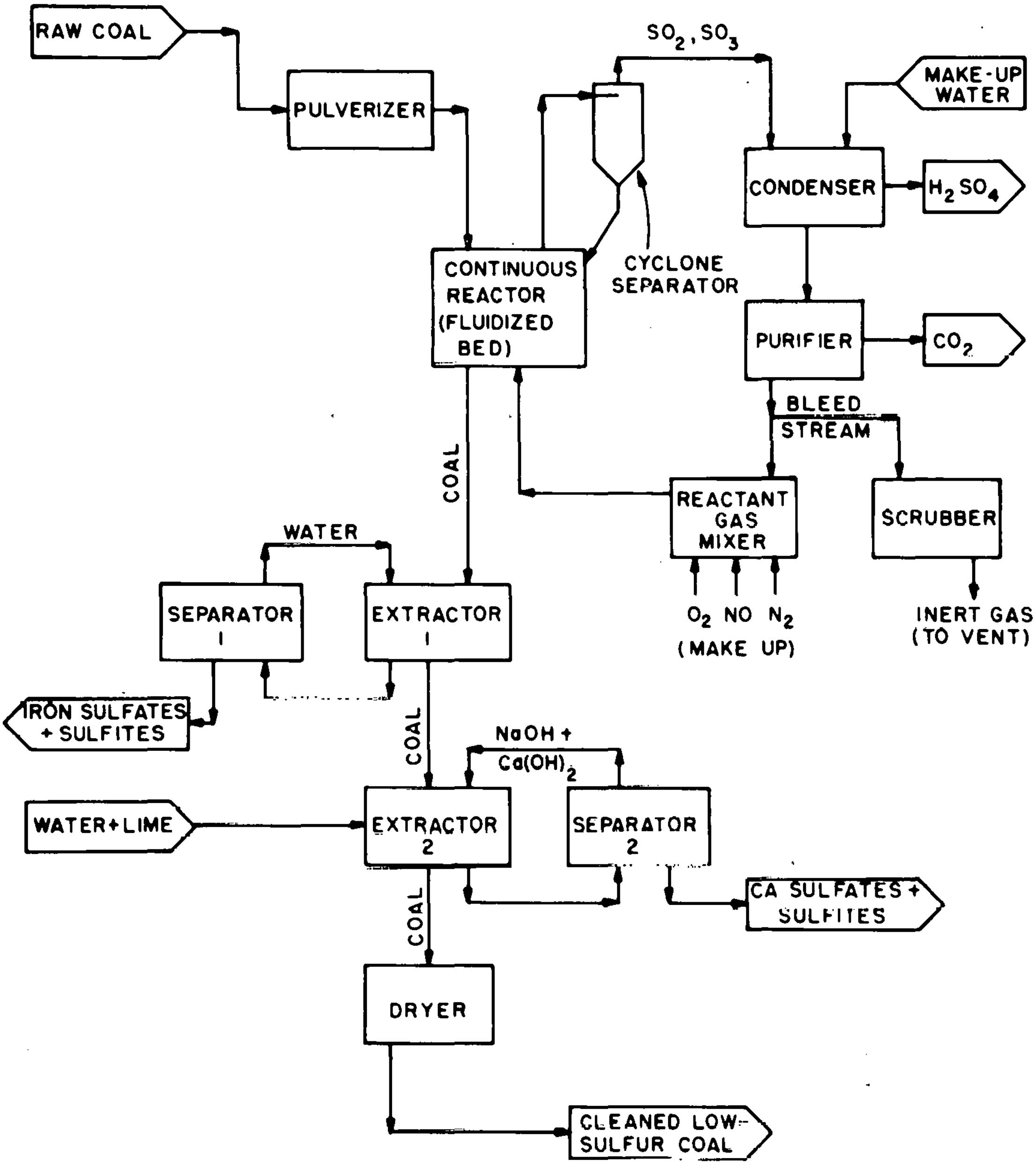


Fig. 4.7. Block flow diagram for the KVB coal desulfurization process.

(0.1 and 2 MPa) and a temperature between 100 and 500°F (38 and 260°C). The composition range of the gas mixture has been given earlier in Sect. 4.6.1. The continuous reactor is proposed to be a fluidized-bed reactor with the four-gas mixture serving as the fluidizing gas.

The gaseous effluents from the reactor are taken to a cyclone separator where the entrained coal particles are separated from the gas stream and returned to the reactor. The gas stream from the cyclone separator is processed further to remove the SO_2, SO_3, and CO_2 gases formed during the reaction with the coal particles. The cleaned gas from the purifier (shown in Fig. 4.7) is mixed with makeup quantities of O_2, N_2, and NO gases and returned to the reactor for reuse. NO_2 is not added with the makeup gases because it is formed by the following equilibrium reaction:

$$NO + 1/2\ O_2 \rightleftarrows NO_2 .$$

The product coal from the reactor is taken through a series of extractors where it is first washed with hot water to dissolve the iron sulfates and sulfites and then washed with an aqueous solution of calcium and sodium hydroxide to extract the organic sulfur compounds present in the coal. Following the second extraction step, the coal is dried to the desired moisture content to yield the low-sulfur product coal.

Liquid solutions from the two extraction steps are processed separately to precipitate the dissolved sulfates and sulfites, as shown in Fig. 4.7. The precipitated chemicals are disposed of appropriately, and the recovered water is reused in the process.

4.7 PERC Oxidative Desulfurization Process

4.7.1 Introduction

Pittsburgh Energy Research Center (PERC) is currently developing a chemical coal desulfurization process that is claimed to remove not only the pyritic sulfur but also a substantial portion of the organic sulfur present in coal. The process is claimed to achieve the above sulfur reductions without sacrificing much of the heat content of the coal. The process has been developed in bench-scale autoclave reactors;

however, further process developments are expected to be conducted in a new, fully continuous unit.

The process consists of reacting finely pulverized (-200 mesh) coal with water and air at high pressures (220 to 1500 psig) and high temperatures (~300 to 430°F) for coal residence times of 1 hr or less. The process is claimed[46] to yield a cleaned product coal that generally contains less than 5% of the original pyritic sulfur and, more importantly, up to 60% less of the original organic sulfur present in the feed coal. The above sulfur reductions are obtained with better than 90% recovery of the original coal's fuel value.

The PERC process is similar to the Ledgemont oxygen leaching process (see Sect. 4.5). The development of the process is still at the bench-scale level. Sufficient information is not yet available to fully assess the merits of the process. However, according to Friedman et al.,[46] preliminary cost estimates made on the process place the cost at $3.50 to $5.00 per ton of coal. These cost estimates appear to be attractively low, considering the claims for the process. However, due to severe time limitations for the present beneficiation study, no independent economic evaluations of the process could be made to verify the validity of the above-stated cost estimates.

4.7.2 Process description

Figure 4.8 is a sketch of the conceptual commercial version of the process. The raw feed coal is first crushed and screened to the proper size (-200 mesh). The sized coal is mixed with water and the recycle dilute H_2SO_4 acid stream in the mixing tank. The coal undergoes mild beneficiation in the mixing tank. Mineral matter associated with the coal is removed in the tank, and the coal-water slurry is pumped to the reactor. In the reactor the slurry is reacted with high-pressure (220- to 1500-psig) air at the desired reaction temperature (~300 to 430°F) for about 1 hr. During the reaction, the sulfur present in the coal reacts with the water and the air to form dilute H_2SO_4. Following the reaction, the coal-dilute acid slurry is filtered to separate the cleaned coal from the dilute acid. The cleaned coal is then dried and taken as the plant product. The dilute acid stream is recycled in the process.

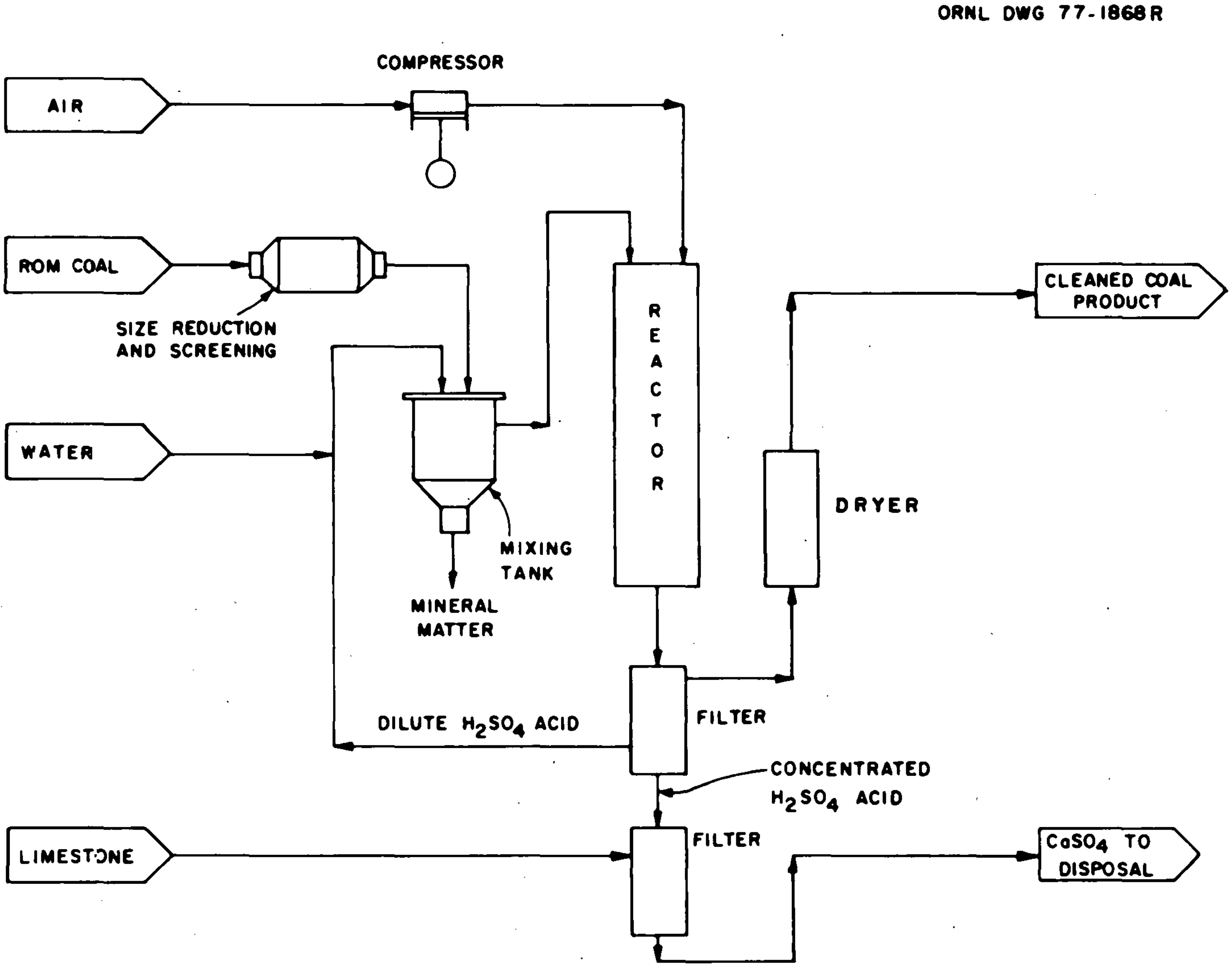


Fig. 4.8. Block flow diagram for the PERC oxidative desulfurization process.

According to Friedman et al.,[46] the acid stream may be recycled up to five times in the process before the acid becomes too concentrated. If a market exists for the concentrated acid, it may be sold as a by-product of the process; if no market exists, the acid can be neutralized with the addition of lime, and the resulting $CaSO_4$ can be filtered and disposed of as a waste product of the process.

4.8 ARCO Process

The Atlantic-Richfield Company (ARCO) process is a bench-scale developmental chemical coal desulfurization process that uses a proprietary oxygen promoter to desulfurize the coal.[47] Very little open information regarding the process is available because ARCO considers the process proprietary. EPRI is providing some of the funds for the process development effort and expects to publish a report on the results to date within the next 2 to 3 months.[48]

Based on the sparse open information available about the process, it appears that the process can remove essentially all the pyritic sulfur and about 20 to 30% of the organic sulfur present in the test coals without incurring a significant loss in the heating value of the coal. No further information regarding the process is available. However, further process development efforts are indicated to be continuing.

4.9 JPL Low-Temperature Chlorinolysis Process

Another process for the desulfurization of coal, a low-temperature chlorinolysis process, is being developed at the Jet Propulsion Laboratory (JPL), California Institute of Technology. Funding for the first phase of the project, which lasted 4 months, was provided by the Coal Preparation Group of the U.S. Bureau of Mines. During this phase, the process chemistry was investigated in a batch-type bench-scale unit. The second phase of the project (expected to be funded by the Solid Fuels Mining and Preparation Division of the Department of Energy) is expected to last 8 months, and during this phase the process chemistry will be investigated in a continuous-flow bench-scale unit.

A block-flow diagram of the process is presented in Fig. 4.9. The process essentially consists of reacting the powdered, moist coal (as a slurry in methylchloroform) with chlorine at 165°F (74°C) and 1 atm pressure for 1 to 4 hr. The coal is then filtered and hydrolyzed with water at 77°F (25°C). The coal from the hydrolysis step is filtered and dechlorinated by heating it at 572 to 662°F (300 to 350°C) and 1 atm pressure for about 2 hr. The methylchloroform (used as the slurry solvent) is recovered and recycled in the process.

Experimental results indicate that the process is capable of removing up to 90% of the pyritic sulfur and up to 70% of the organic sulfur present in the high-sulfur bituminous coals tested. The above sulfur reductions are obtained with a loss of coal heating value of less than 2%.

Although the development effort is still at the bench-scale level, the process appears to have the potential of becoming a viable coal beneficiation process. However, aside from the economics of the process, several questions need to be addressed regarding the process chemistry — questions such as the concentration of residual chlorine in the product coal and its effect on the downstream processing of the beneficiated coal. These questions are proposed to be resolved in the subsequent phases of the project.

5. MICROBIAL BENEFICIATION METHODS

5.1 Introduction

Microbial coal beneficiation methods, as the name implies, involve the use of bacterial strains to oxidize and remove the pyritic sulfur present in coal. The bacteria involved in the process belong to the acidophilic group of bacteria known as the *Thiobacillus ferrobacillus* group. This bacterial group includes the following bacteria:

1. *Thiobacillus ferrooxidans*, also known as *Ferrobacillus ferrooxidans*, and
2. *Thiobacillus thiooxidans*.

ORNL DWG 77-2069

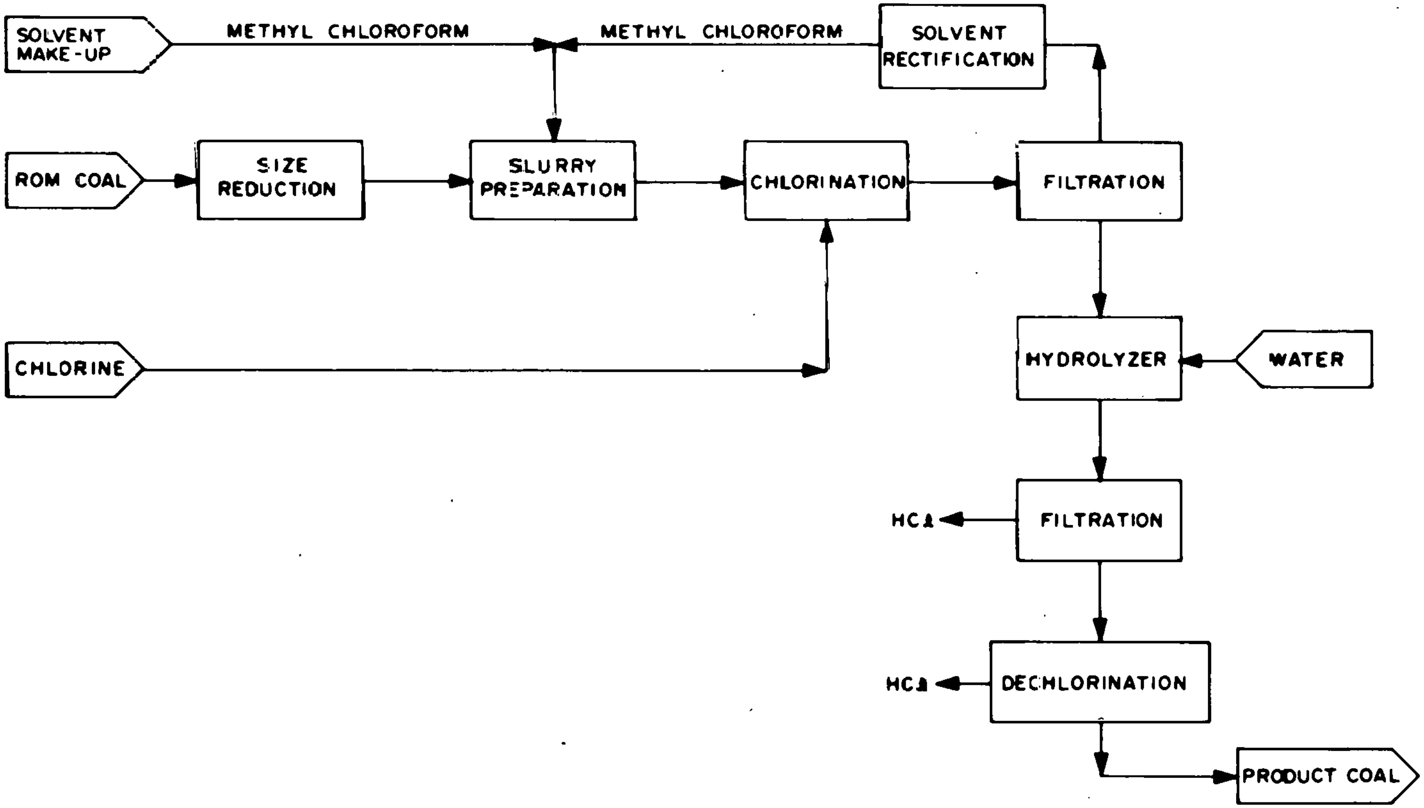


Fig. 4.9. Block flow diagram for the JPL low-temperature chlorinolysis process.

Laboratory studies[49,50] have indicated that *Thiobacillus thiooxidans* does not attack pyrites. However, *Ferrobacillus ferrooxidans* strains readily oxidize the pyrites present in coal, given the appropriate environment.

The microbial oxidation process normally occurs as follows: In the presence of water and oxygen and, given the correct acidity level of the solution, the bacteria oxidize the FeS_2 present in coal to form ferric sulfates and sulfuric acid. The bacteria do not attack the coal or the organic sulfur present in the coal. Hence the process is not very effective as a beneficiation process for coals having a high organic sulfur content. Also, the process only removes that mineral matter from the coal which is dissolved by the acidic environment. The process is known to occur in nature during the weathering of coal and mine wastes. In fact, this process occurs to the extent that several studies have been reported in the literature on methods of inhibiting the bacterial growth with a view of minimizing the acidic drainage from mine wastes. However, only recently has the process been evaluated with the viewpoint of developing a coal beneficiation process. The studies to date have been at the bench-scale level of development. No studies are reported in the literature where a conceptual commercial-scale plant has been developed that uses bacteria for the beneficiation of coal.

5.2 Results of Laboratory Studies

Silverman, Rogoff, and Wender[51] conducted extensive bench-scale studies at the U.S. Bureau of Mines to determine if the microbial oxidation of pyrites could be used on a commercial scale for the beneficiation of coal. They evaluated several different types of coals ranging in rank from lignite to bituminous. Based on their studies, they concluded that:

1. Appreciable quantities of pyrites could be removed from all the coals they evaluated by the action of the acidophilic bacteria *Ferrobacillus ferrooxidans*. They reported up to 80% pyritic sulfur removal from some of the coals.

2. The oxidation of the pyrites increased as the coal particle size was decreased. For example, in one of their experimental runs, the percentage of pyrites removed by the bacterial action increased from 2.1% for coal particles in the -100 +200 mesh size range to 68.2% for particles in the -325 mesh size range.
3. The microbial action appeared to be most rapid when the pH range of the microbial environment was kept between 2.5 and 4.2 — that is, a highly acidic environment.
4. The oxidation or removal rate of the pyrites by the bacteria is apparently affected by the neutralizing capacity or the basicity of the coal. The basicity of the coal tended to increase as the coal rank decreased; that is, lignites tended to be more basic in nature than the bituminous coals tested. Hence, the pyrite removal rate decreased as the coal rank decreased.
5. The depyritization rate of the bacteria was very slow. The bacterial reaction took 3 to 4 days to achieve the pyritic sulfur removals reported.
6. Acid pretreatment of the coals improved the depyritization rate. Apparently, the presence of large quantities of $CaCO_3$ or other basic materials tended to inhibit the bacterial oxidation of the coal.

5.3 Conclusions and Recommendations

The following conclusions can be made regarding the microbial beneficiation of coal:

1. The pyrite contents of most coals can be reduced significantly by the action of the acidophilic bacteria *Ferrobacillus ferrooxidans*.
2. These bacteria occur naturally in coals and mine wastes.
3. The depyritization ability of the bacteria is very dependent on the pH of the environment, being most effective for solutions with a pH value of 2.6 to 4.2.

4. The pyrite removal efficiency of the bacteria increases as the coal rank increases and the particle size decreases. High pyrite removal can be obtained for fine-sized (-325 mesh) bituminous levels.
5. The microbial process results in the production of ferric sulfates and H_2SO_4. The disposal of these waste products may pose an environmental problem for a large-scale commercial facility.

It is recommended that:

1. Laboratory-scale studies should be continued to develop a better understanding of the microbial oxidation process, especially from the viewpoint of reducing acidic wastes from coal mine reject piles. Efforts should also be undertaken to identify or develop new bacterial strains that may be able to depyritize the coal at a faster rate and/or be able to reduce the organic sulfur content of the coal.
2. Economic evaluations should be conducted of a conceptual commercial-scale plant based on the microbial desulfurization process to determine its commercial viability.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

6. APPENDIXES

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

Appendix A: Basis for the Economic Analysis of Coal Beneficiation Processes

A.1 Introduction

The economic analysis for the various coal beneficiation processes evaluated was performed by using ORNL-developed economic analysis computer program PRP.[52] The price of the cleaned product coal from the various beneficiation processes was determined using the discounted cash flow (DCF) rate of return method under the following conditions:

1. ROM coal costs ranged between $10/ton and $50/ton.
2. No costs were included for a captive coal mine.
3. All costs were developed in terms of January 1977 dollars. No forward escalation beyond January 1977 was included in the costs
4. Debt/equity ratios of 0:100, 30:70, 70:30, and 95:5 were used.
5. Annual after-tax rate of return (AARR) on equity capital was 10, 12, 15, 17, and 20%. However, for reasons of conciseness, only the results for 12 and 15% AARR on equity capital are reported.
6. Annual interest rate on the debt fraction of the capital was assumed to be 9%.

Results of the economic analyses were developed as plots of the cleaned product coal price for various ROM coal costs and debt/equity ratios. A selected, representative set of these plots is presented cumulatively in Appendix B of this report.

The basic premises used for the economic analyses are summarized in the following sections.

A.2 Premises for the Economic Evaluation of Coal Beneficiation Processes

The premises for the economic evaluation are presented as (1) capital investment--related items, (2) operating costs--related items, and (3) economic evaluation procedure--related items.

A.2.1 Capital investment--related items

1. Direct plant costs. Direct plant costs were developed for each beneficiation process evaluated for proposed plants capable of producing 1500- and 15,000-ton/day maf product coal. In general, the costs developed were order-of-magnitude type costs. The probable accuracy of the cost estimates is ~±30%. The costs were developed for grassroots-type facilities,with raw water being the only available utility. Capital costs for generating the other utilities required in the plant were included in the direct plant cost. Direct plant costs were also developed for the battery-limits type facilities where all the utility requirements were purchased.

2. Engineering and contractor's fee. A sliding scale was used to estimate the engineering and contractor's fee. The scale used is given below:

Project cost ($\$10^6$)	Engineering and contractor's fee (% of direct plant cost)
0-100	15
101-1000	8

3. Contingency. Contingency costs were estimated as 15% of the total direct plant cost. Process and/or project contingencies (where applicable) are included in this cost. However, since the estimates were made in terms of constant dollars, the contingency does not include any allowance for the time escalation of costs.

4. Start-up plant modifications. Plant modifications that may be necessitated during the start-up phase were estimated to be 2% of the direct plant cost.

5. Working capital. Working capital requirements were estimated to be the sum of the following items:

- 20 days of feedstock coal at $20/ton of ROM coal,
- 30 days of product coal value at $30/ton of product coal, and
- 30 days of gross plant operating costs.

More information regarding the working capital is presented in Sect. A.2.3.

6. Land. Land costs were estimated at $2000 per acre.

A.2.2 Operating costs — related items

1. Utilities. For the grassroots-type facilities, the only utility premised to be available to the beneficiation plant was raw water. All other plant utility requirements were assumed to be generated onsite. Capital cost for utility-related equipment is included in the cost of the offsite facilities in the capital investment cost estimate. Fuel requirements for generating some of the utilities were provided by burning a small fraction of the beneficiated coal product. In addition, process and cooling water costs were estimated at $0.50/kgal and $0.05/kgal respectively. These costs were intended to reflect the cost of pumping, storing, and treating the water used in the process. For the battery-limits type facilities, on the other hand, all the utility requirements were premised to be purchased. In addition to the above costs for the process and cooling water, the following costs were premised for the other plant utilities:

Electric power	2.5¢ per kWhr
Steam	$1.90 per 1000 lb

2. Chemicals and catalysts. The costs of the chemicals and catalysts used were determined for each process (and plant) based on the requirements developed in the process design. The costs per unit of the chemicals and catalysts used are individually reported for each process evaluated.

3. Operating labor costs. These costs were subdivided into the following two groups:

- process operating labor cost, and
- supervisory personnel cost.

Process operating labor cost. Because the complexity of each beneficiation process was unique, the process operating labor costs were estimated individually for each beneficiation process using the labor rates presented below as guidelines.

Location	Operating labor rates ($/man-hour)
Eastern United States	7.50
South and south central United States	7.00
Midwestern United States	7.50
Western United States	7.00
West coast United States	8.00

Supervisory personnel cost. These costs were estimated to be 20% of the process operating labor cost for each plant.

4. Labor burden. The labor burden was estimated to be 35% of the operating labor costs. Labor burden includes the associated costs of social security contributions, unemployment insurance contributions, sick pay, vacation pay, other fringe benefits, and shift differentials.

5. Plant maintenance costs. Plant maintenance costs were estimated to be 5% of the depreciable capital investment. This includes the cost of maintenance labor, materials, labor supervision, and the labor burden for the maintenance crew.

6. Operating supplies. The cost of operating supplies was estimated to be 30% of the process operating labor cost.

7. General administrative overhead costs. These were estimated to be 40% of the sum of the process operating labor, plant maintenance, and operating supplies cost indicated above. This includes the cost of services (other than those directly related to the plant production)

that are generally necessary for the efficient operation of the plant, such as hospital and medical services, general engineering services, secretarial services, janitorial services, etc.

8. Waste disposal cost. Waste disposal costs were estimated to be $1 per ton of waste product to be disposed.

9. Property insurance cost. Property insurance cost was estimated to be 1% of the total depreciable capital, including the cost of start-up modifications--related capital equipment.

10. By-product credits. Credits for salable by-products from each beneficiation process were developed individually based on the process design. In general, however, for those processes where sulfur was generated as a salable by-product, its credit was allocated at $60 per long ton.

11. Other costs. Other operating costs nominally include taxes, depreciation, and interest on invested capital during the construction phase of the plant. These costs are accounted for as part of the cash flow analysis performed by the computer program and will be discussed in the next section.

A.2.3 Economic evaluation procedure — related items

1. General. The economic evaluation of the coal beneficiation processes was performed for two plant sizes (namely, plants designed to produce 1500 and 15,000 tons/day maf product coal) for each beneficiation process using ORNL's computer program PRP. The objective of the economic evaluation was to determine the price of the cleaned coal produced as a function of the ROM coal cost, the type of financing used, and the annual after-tax rate of return on the equity capital. The computations were made using the DCF rate of return method.

2. ROM coal costs. ROM coal costs were varied from $10 per ton to $50 per ton in $10-per-ton increments.

3. Financing. The following debt/equity ratios were used in the economic evaluation: 0:100, 30:70, 70:30, and 95:5. Annual interest rate on the debt fraction of the capital was assumed to be 9%, and 10, 12, 15, 17, and 20% annual after-tax rates of return were used for the

equity fraction of the capital required for the proposed beneficiation facilities.

4. Project life. The project life was assumed to consist of a construction period followed by a plant operating period of 20 years. A 2-year construction period was assumed for the 1500-ton/day facility, while a 4-year construction period was assumed for the 15,000-ton/day plant. The following capital spending schedule was assumed to occur for the two plant sizes:

Year	Spending schedule (% of depreciable capital investment per year) 1500-ton/day plant	15,000-ton/day plant
1	50.0	5.0
2	50.0	20.0
3		45.0
4		30.0
Total	100.0	100.0

5. Interest on capital during construction. The capital invested during the construction period was assumed to earn interest at the same rate as during the years following the start-up of the proposed plant. Because there is no income generated by the plant prior to start-up, the interest that accrued on the capital was accumulated and added to the outstanding capital that was to be recovered during the plant operating years. For tax purposes, interest on debt was treated as a deductible expense in the year in which it was paid. The above procedure is accounted for internally in the computer program PRP.

6. Depreciation. Depreciation was not included as an operating cost because the recovery of the capital is accounted for within the discounted cash flow analysis procedure. For tax purposes, depreciation was calculated by the sum-of-the-years' digits method using a depreciable life of 16 years for the process facilities. Depreciation life was assumed to start at the end of the construction period.

7. Taxes. Taxes were accounted for in the computer program as part of the cash flow analysis. The following tax rates were assumed:

- federal income tax — 48%,
- state income tax — 3%,
- state revenue tax — 0%,
- local property tax — 2%.

An investment tax credit of 10% of the depreciable capital was also assumed in the economic analysis.

8. Working capital. The working capital was assumed to be invested at the beginning of the project and was assumed to be recovered intact at the end of the project life.

9. Salvage value. The salvage value of the plant was assumed to be zero at the end of the project life.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

Appendix B: Calculated Cleaned Product Coal Price Plots

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

B.1 Plots for Wet Mechanical Beneficiation — Mild-Cleaning Plants

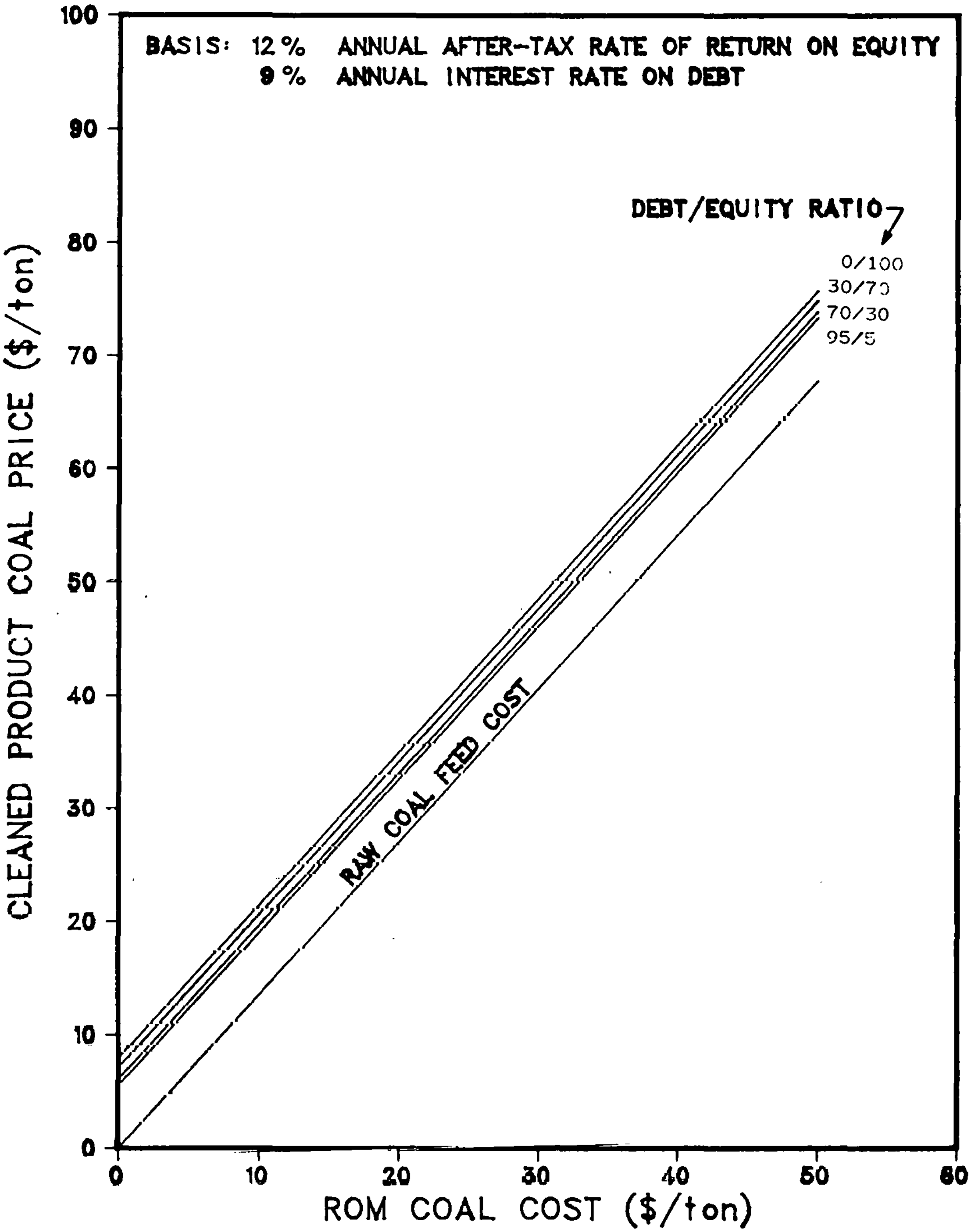


Fig. B-1. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

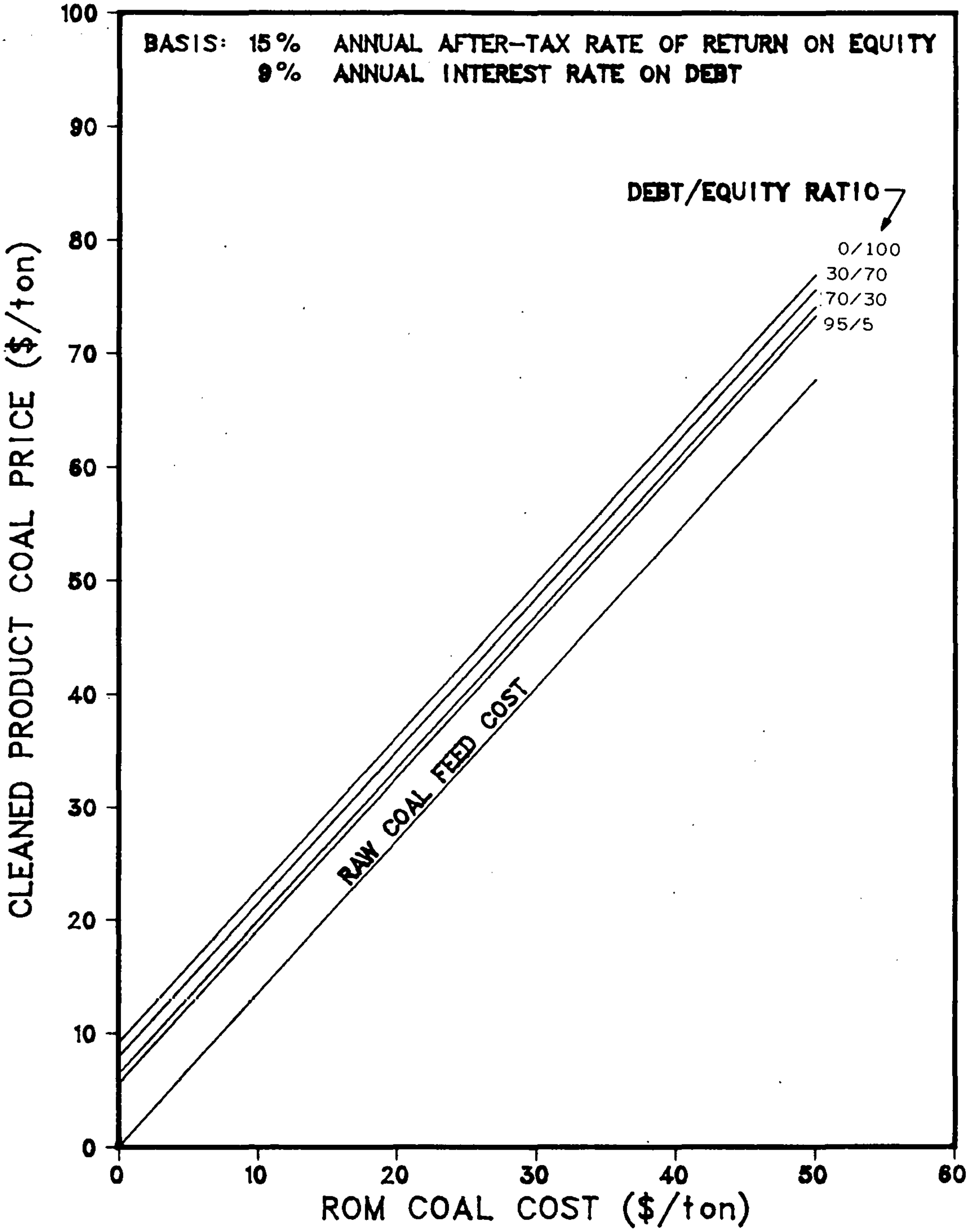


Fig. B-2. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

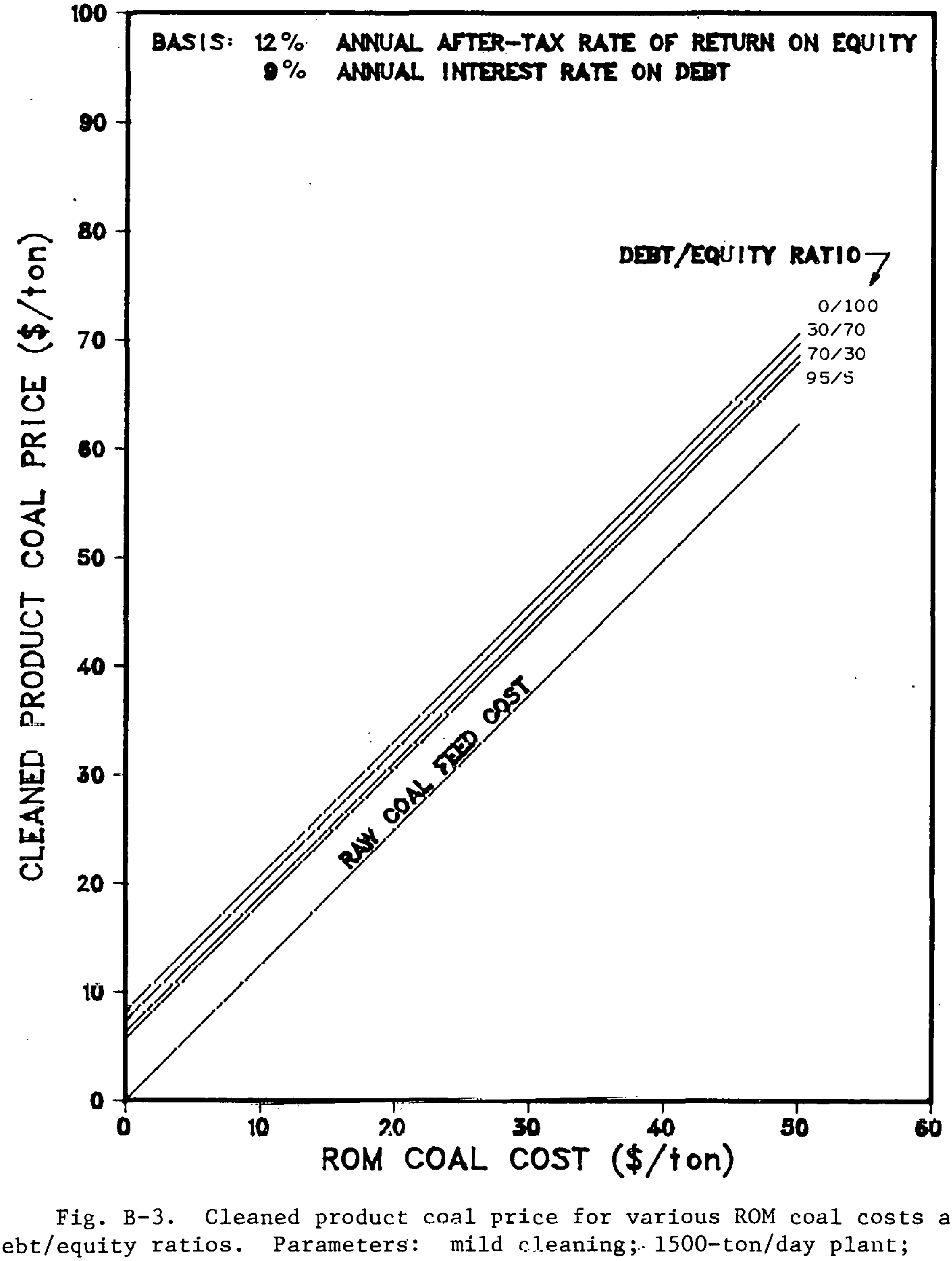


Fig. B-3. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

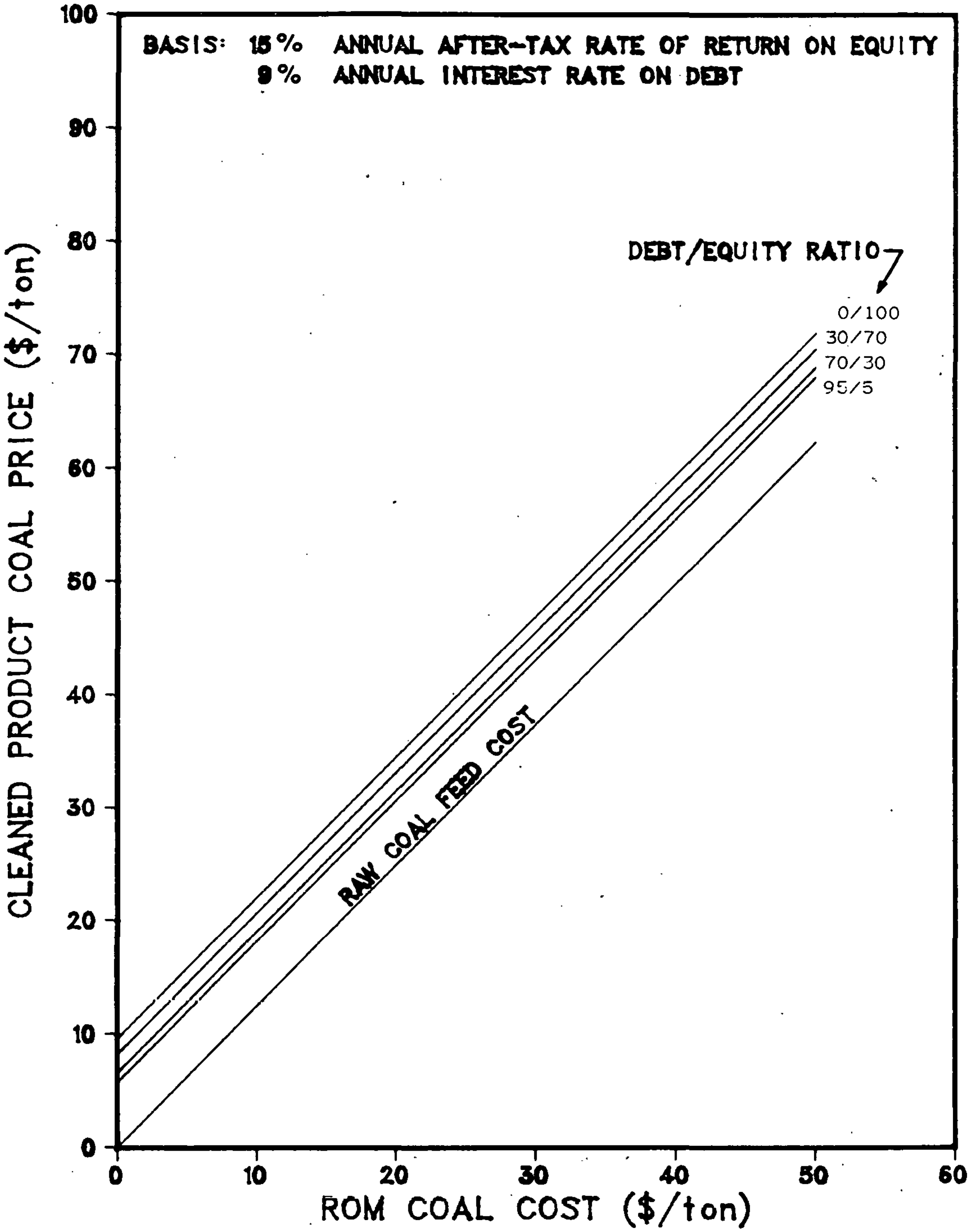


Fig. B-4. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

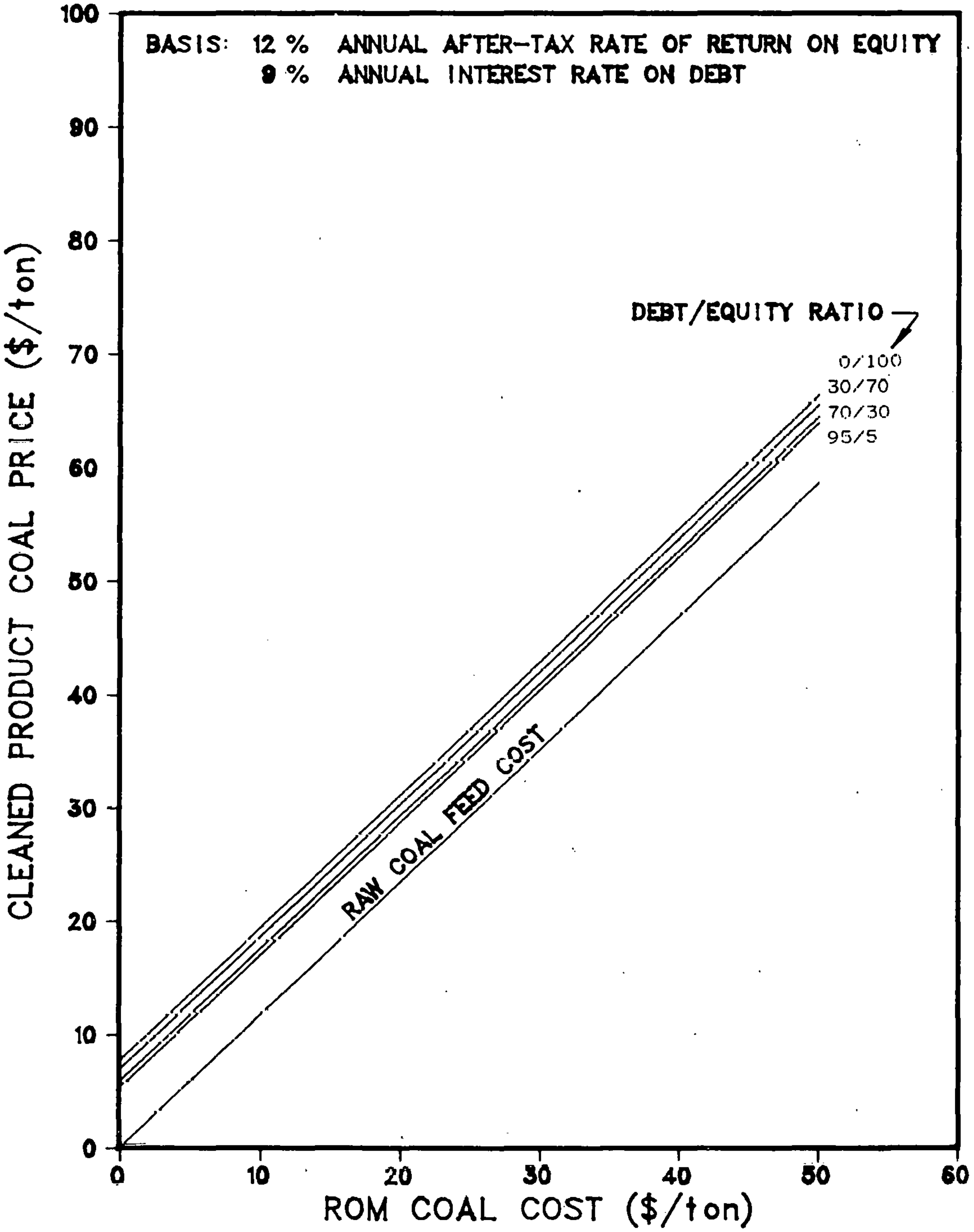


Fig. B-5. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

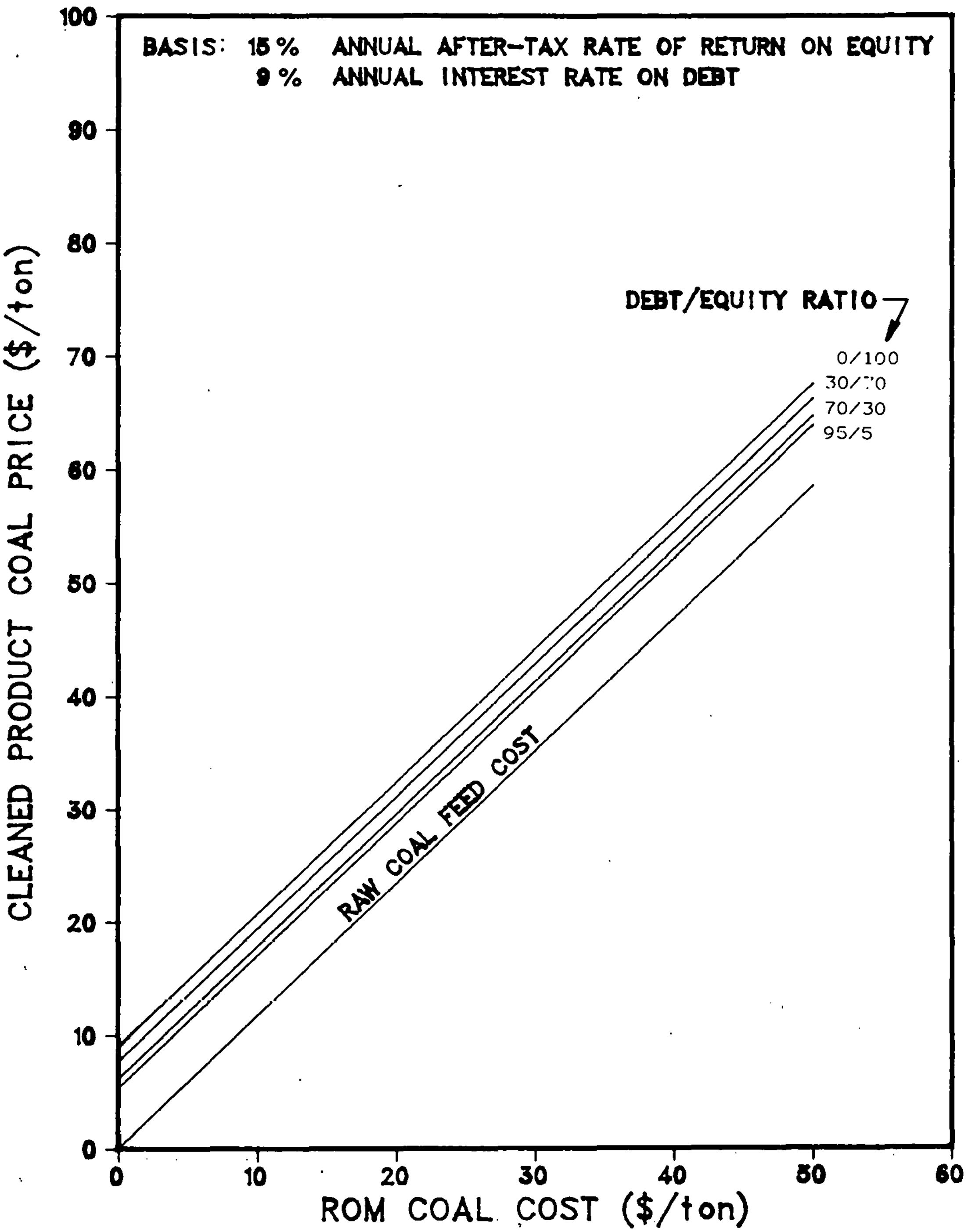


Fig. B-6. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

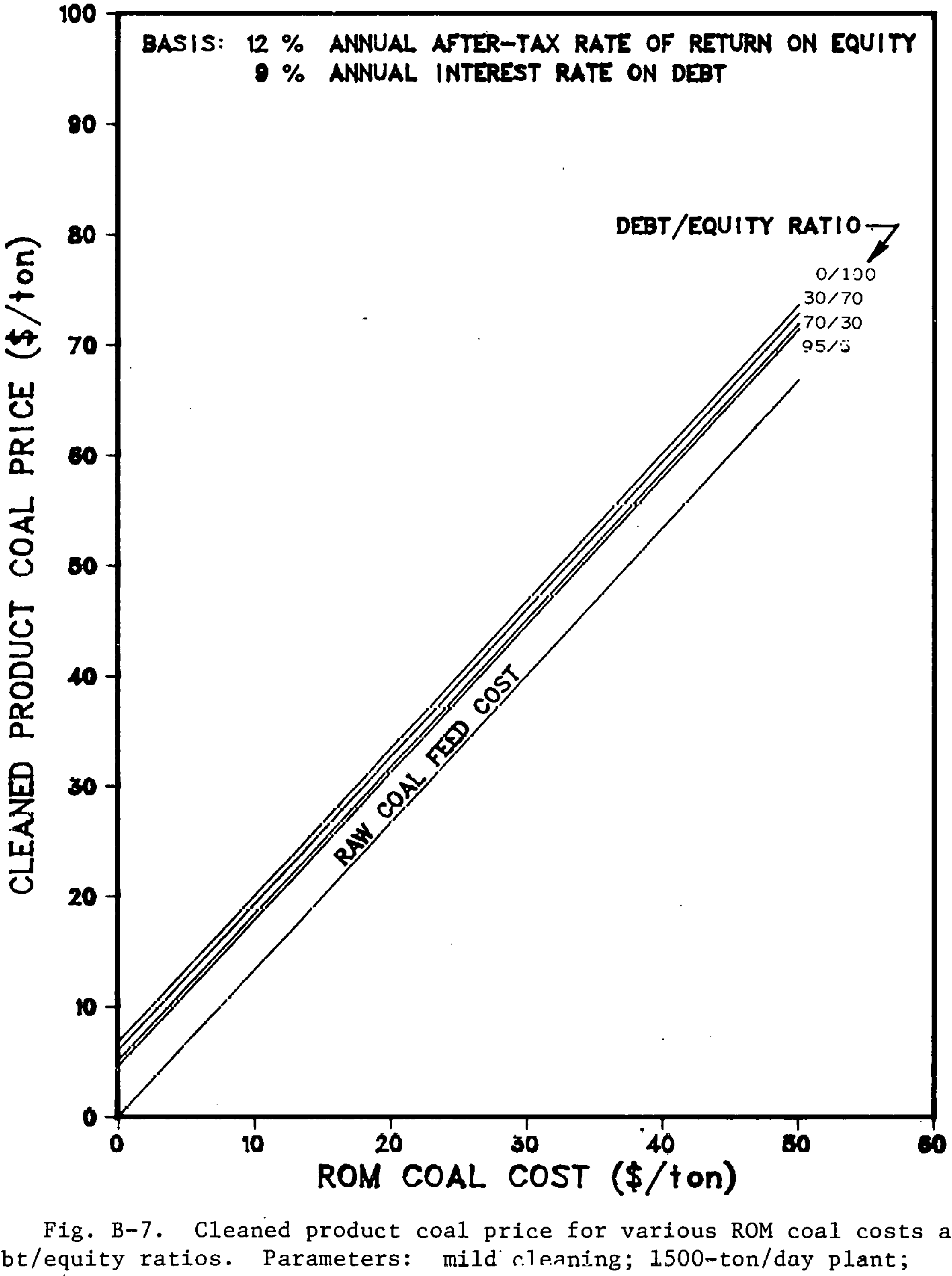


Fig. B-7. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

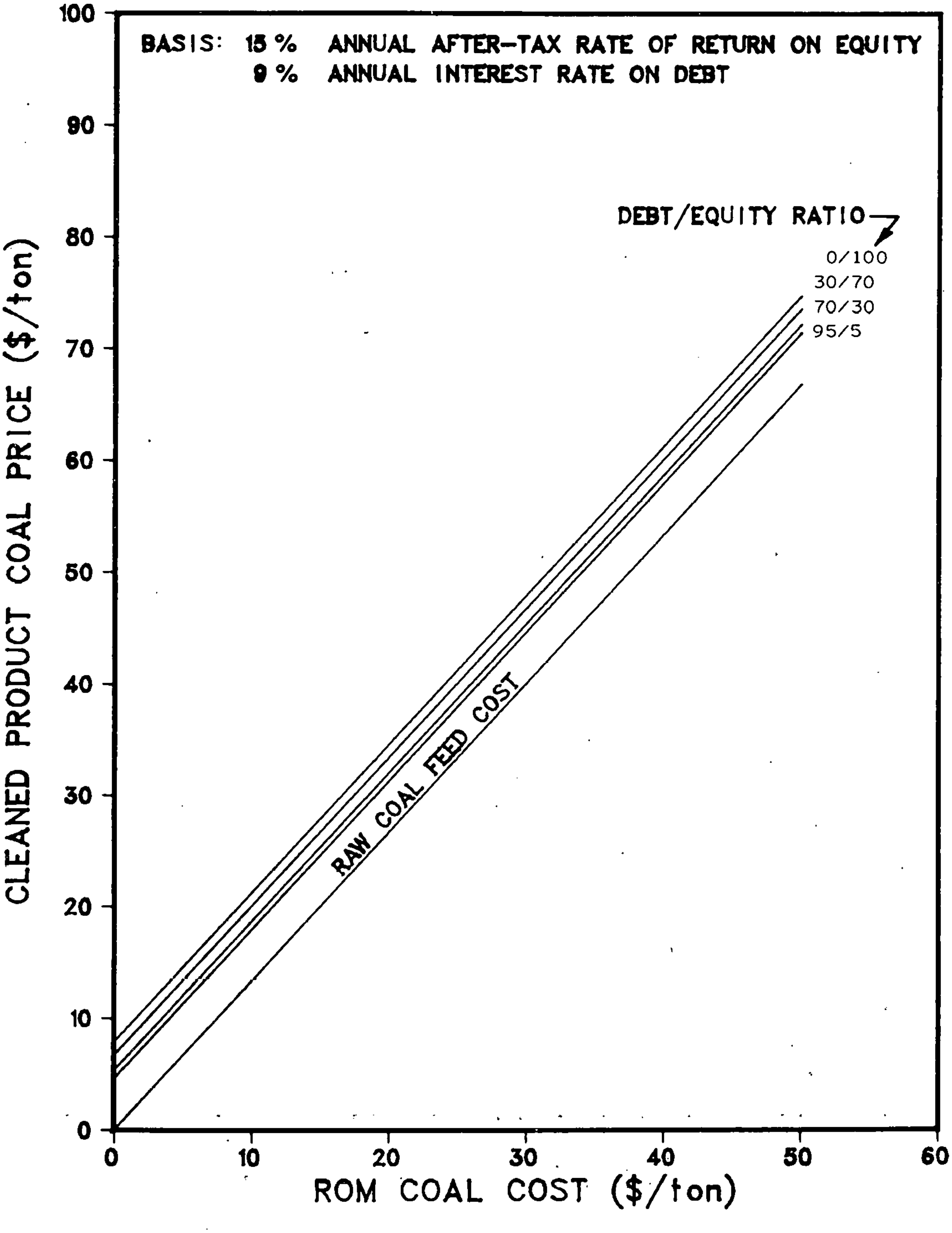


Fig. B-8. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

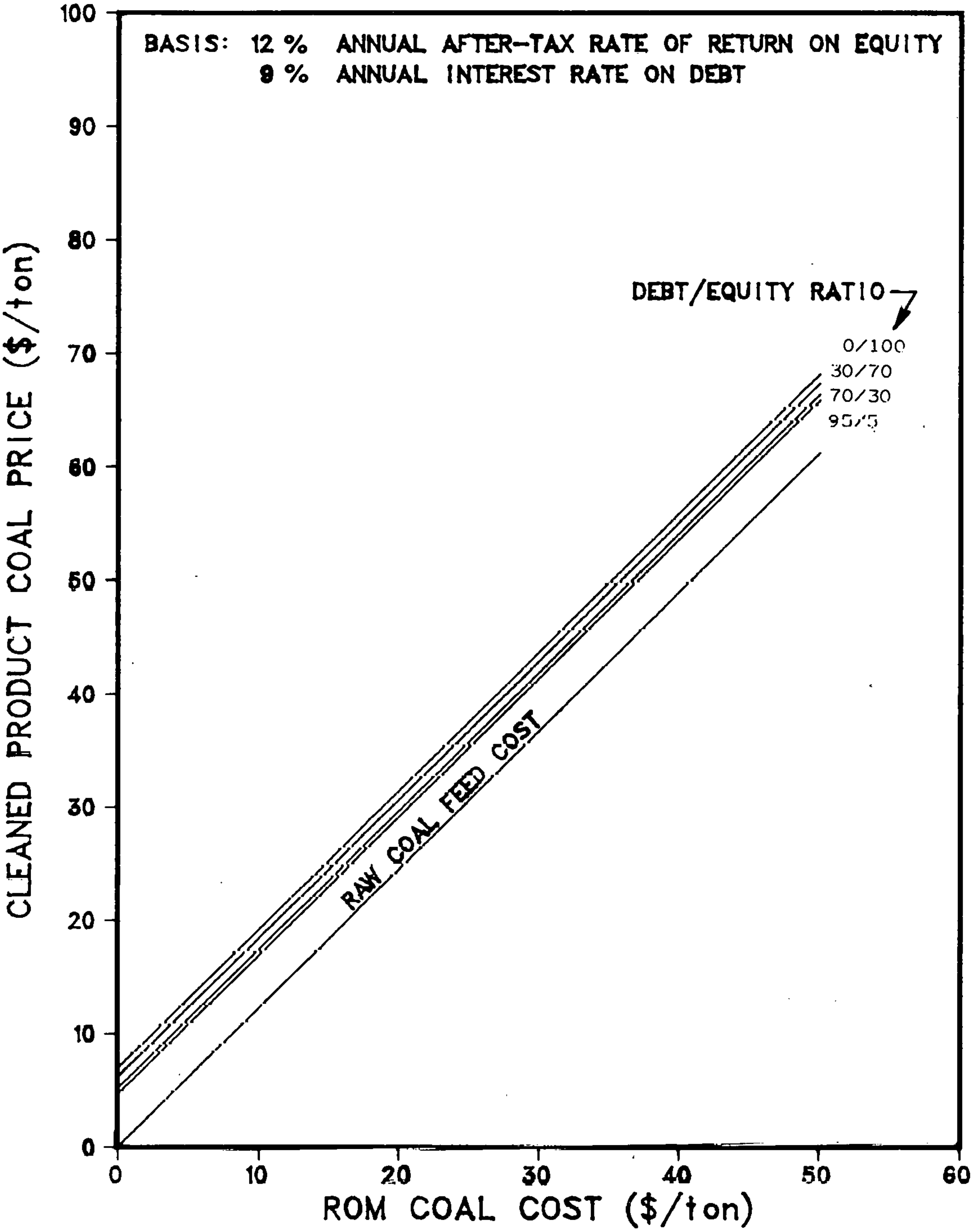


Fig. B-9. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

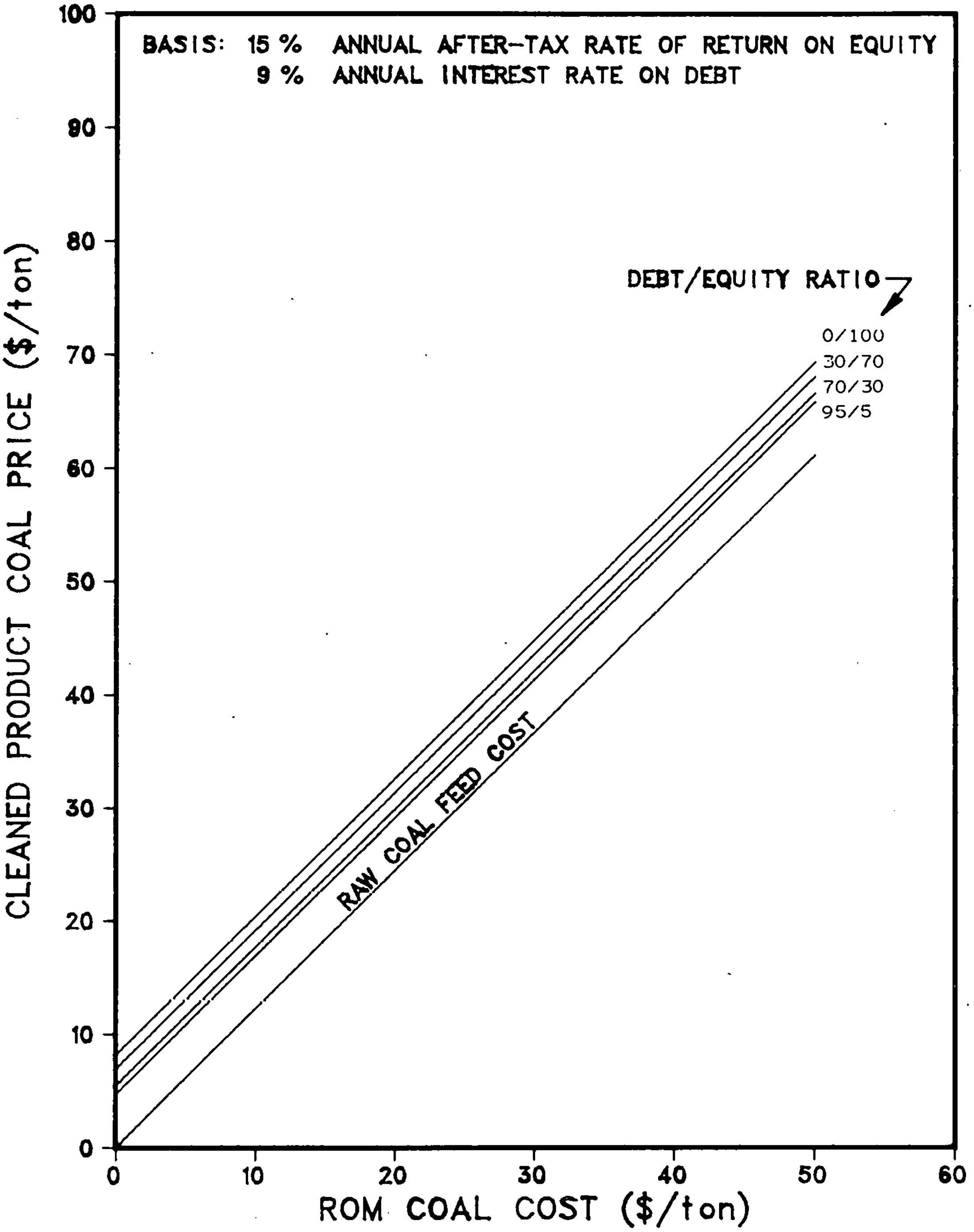


Fig. B-10. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

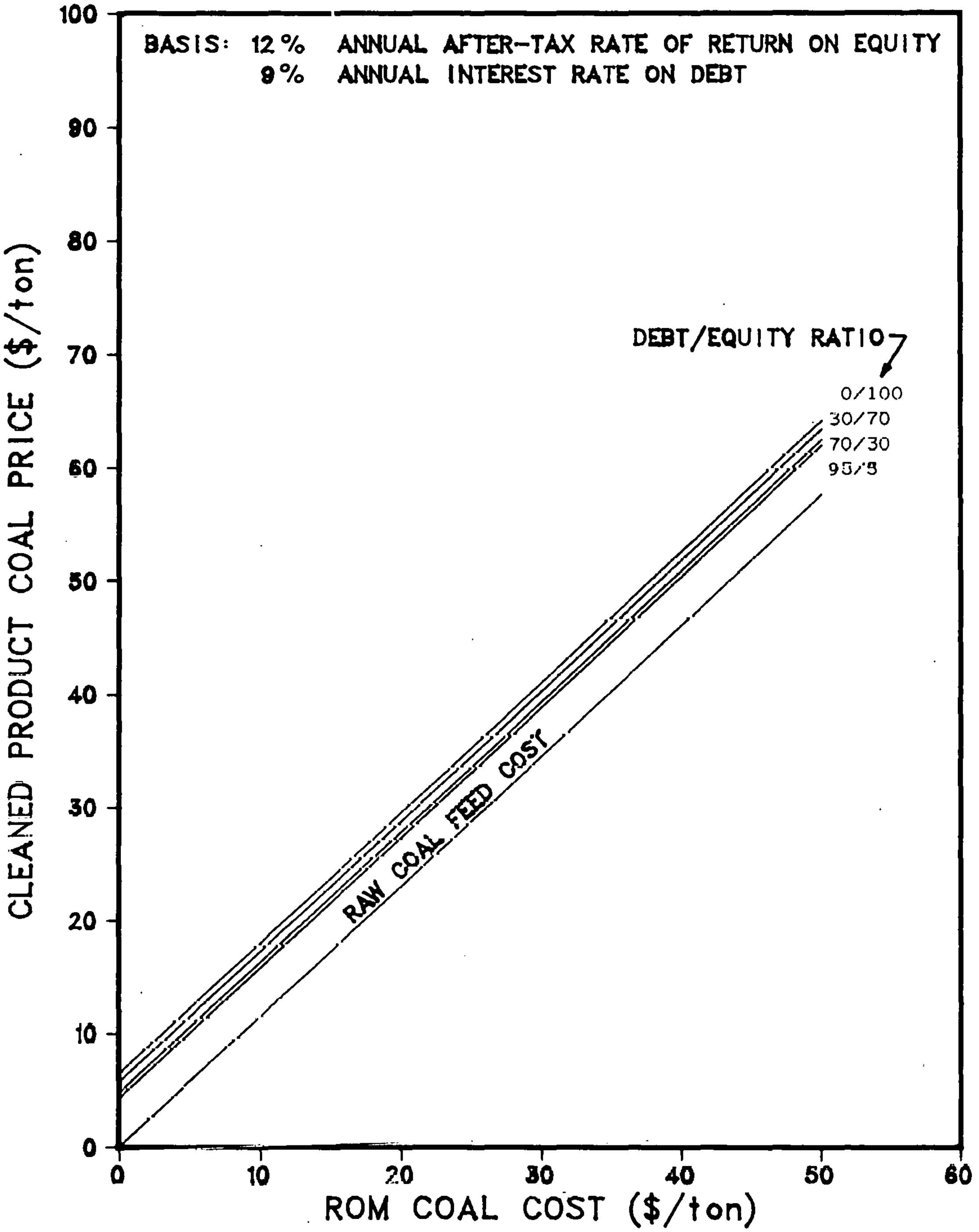


Fig. B-11. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

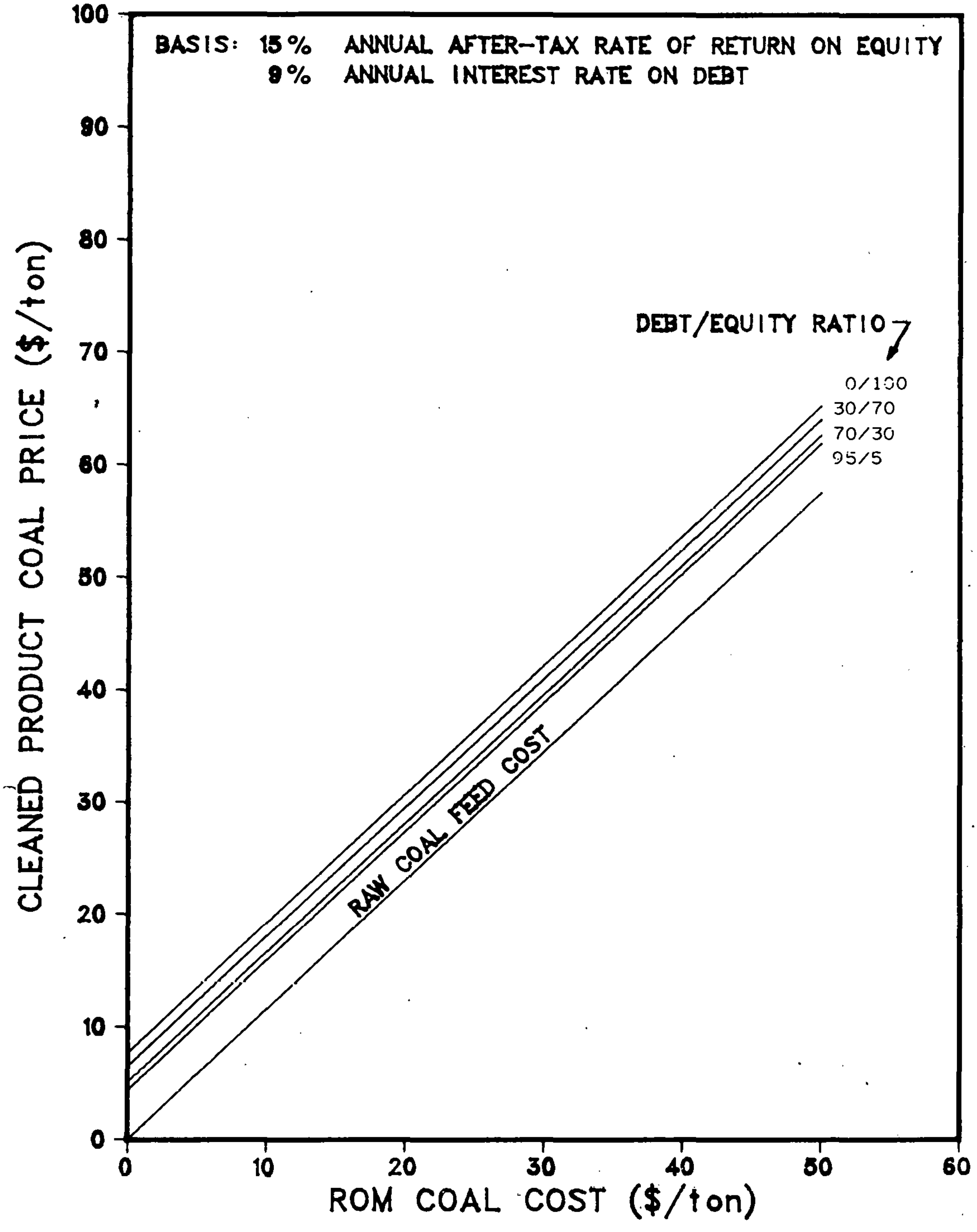


Fig. B-12. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 1500-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

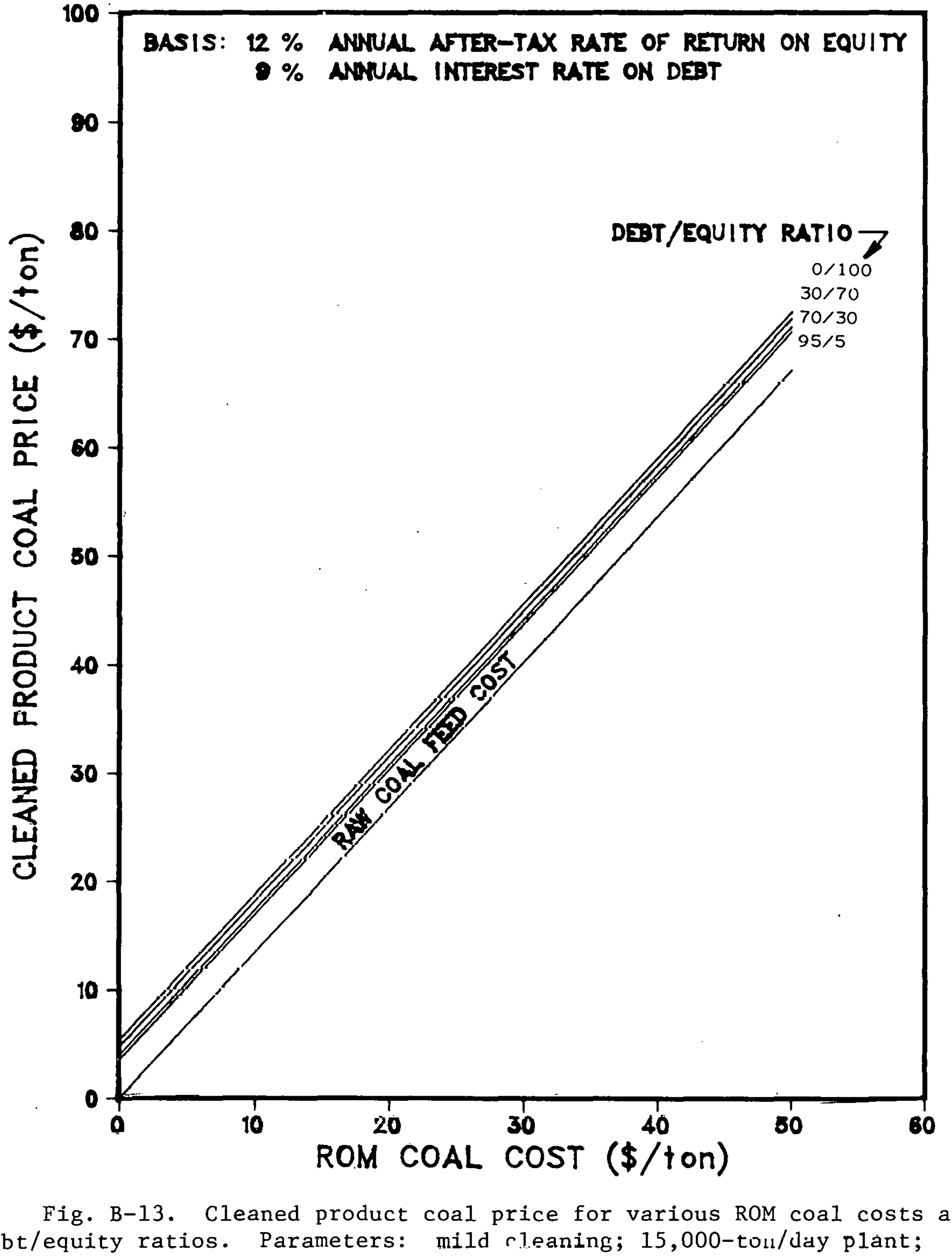


Fig. B-13. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

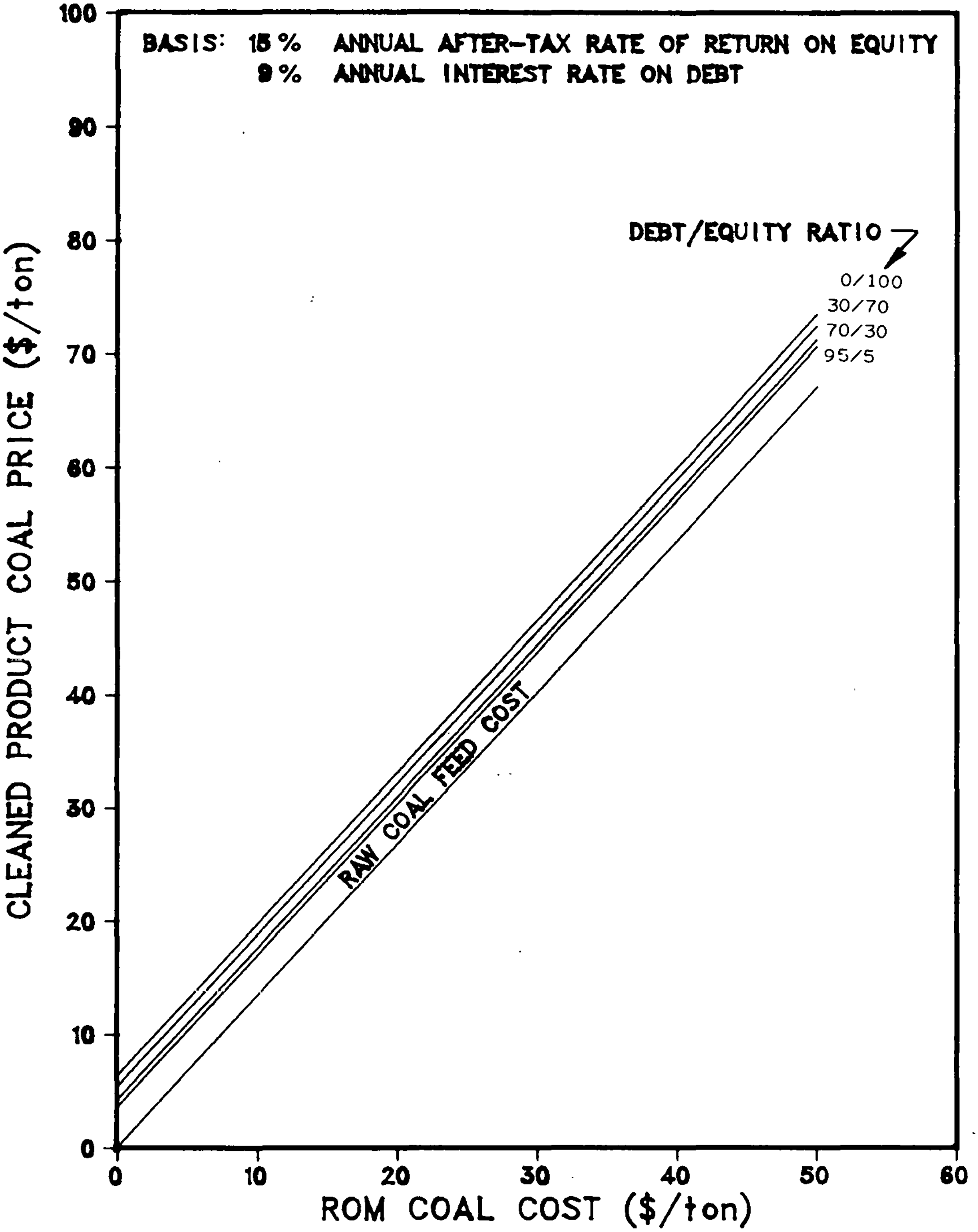


Fig. B-14. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

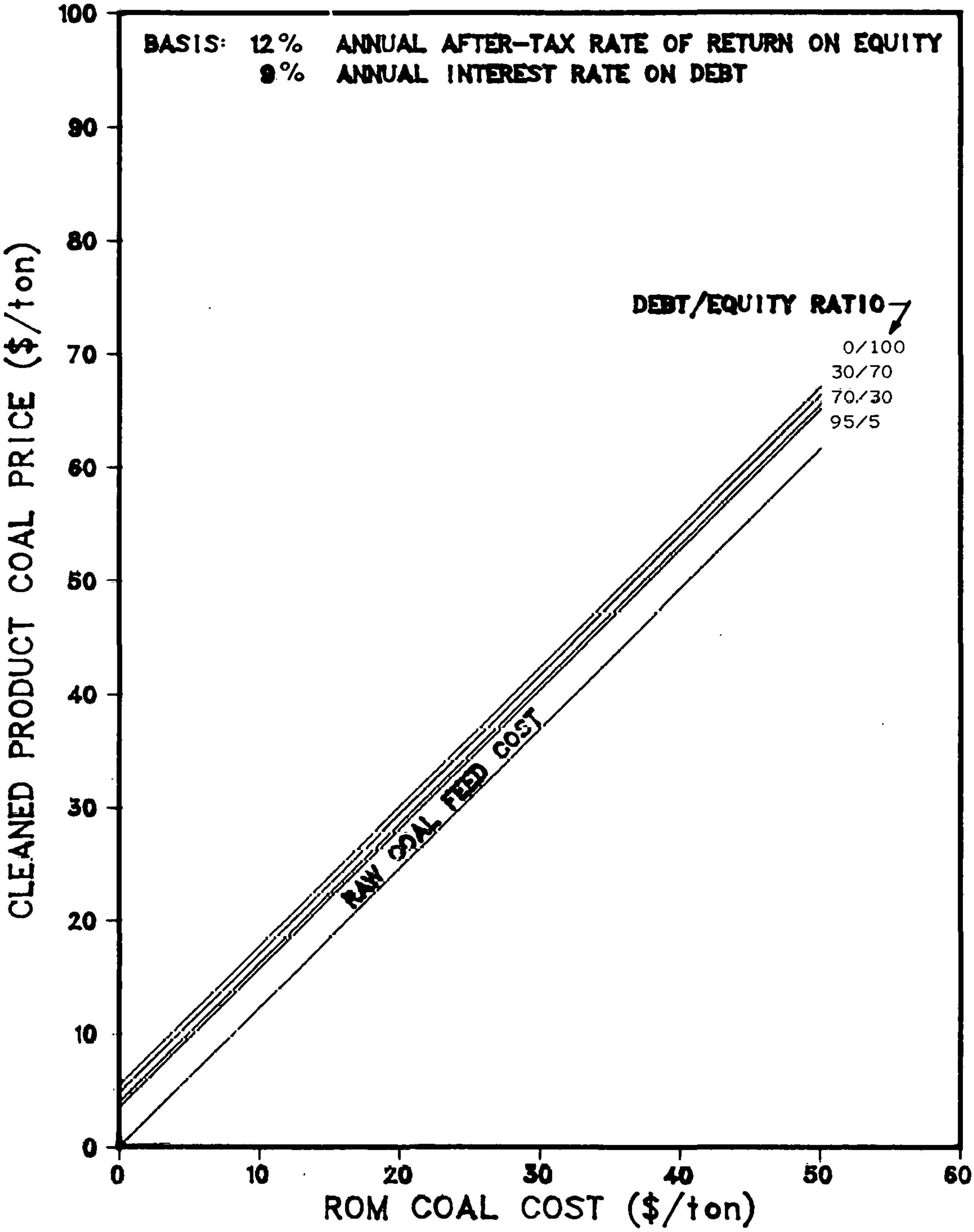


Fig. B-15. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

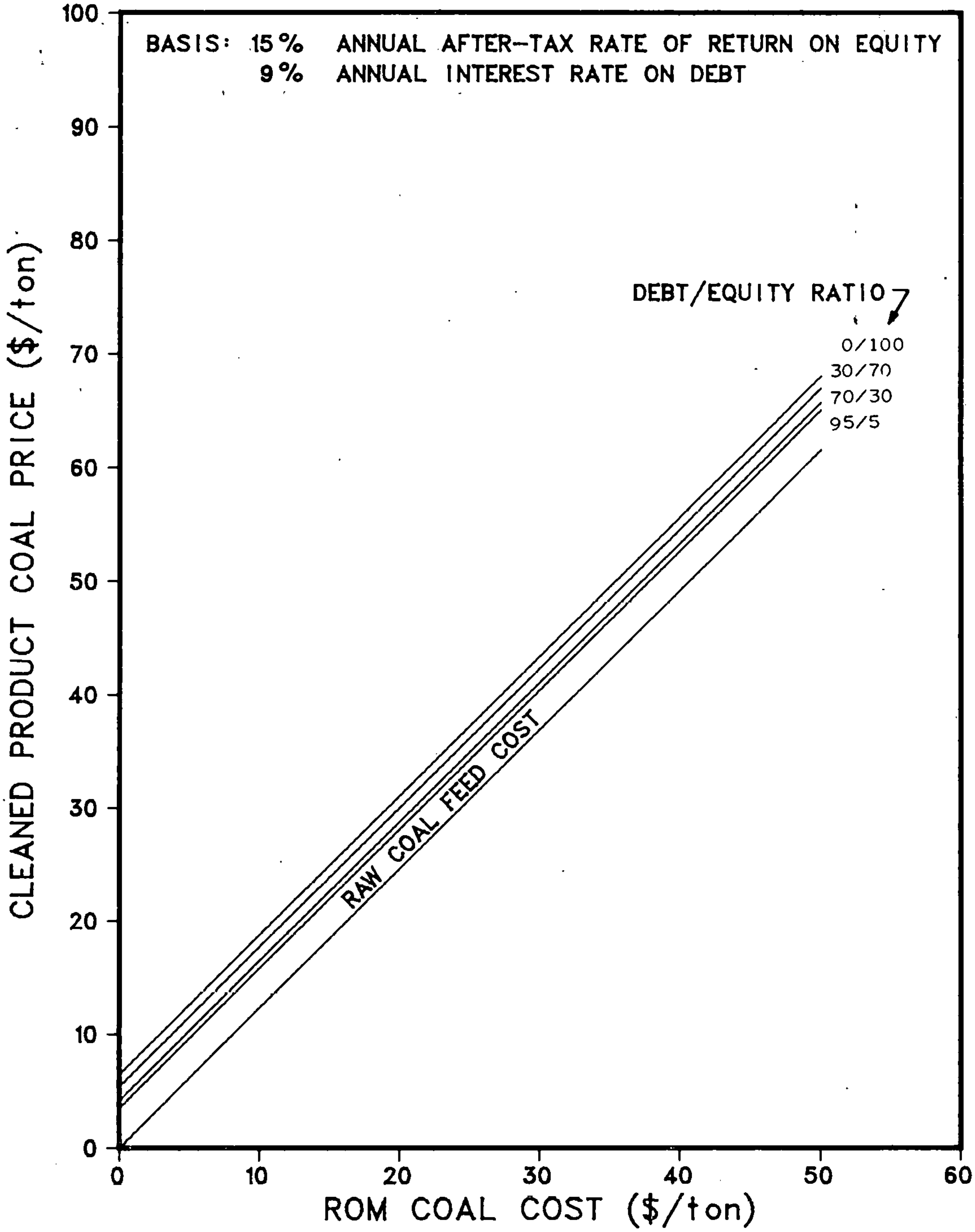


Fig. B-16. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

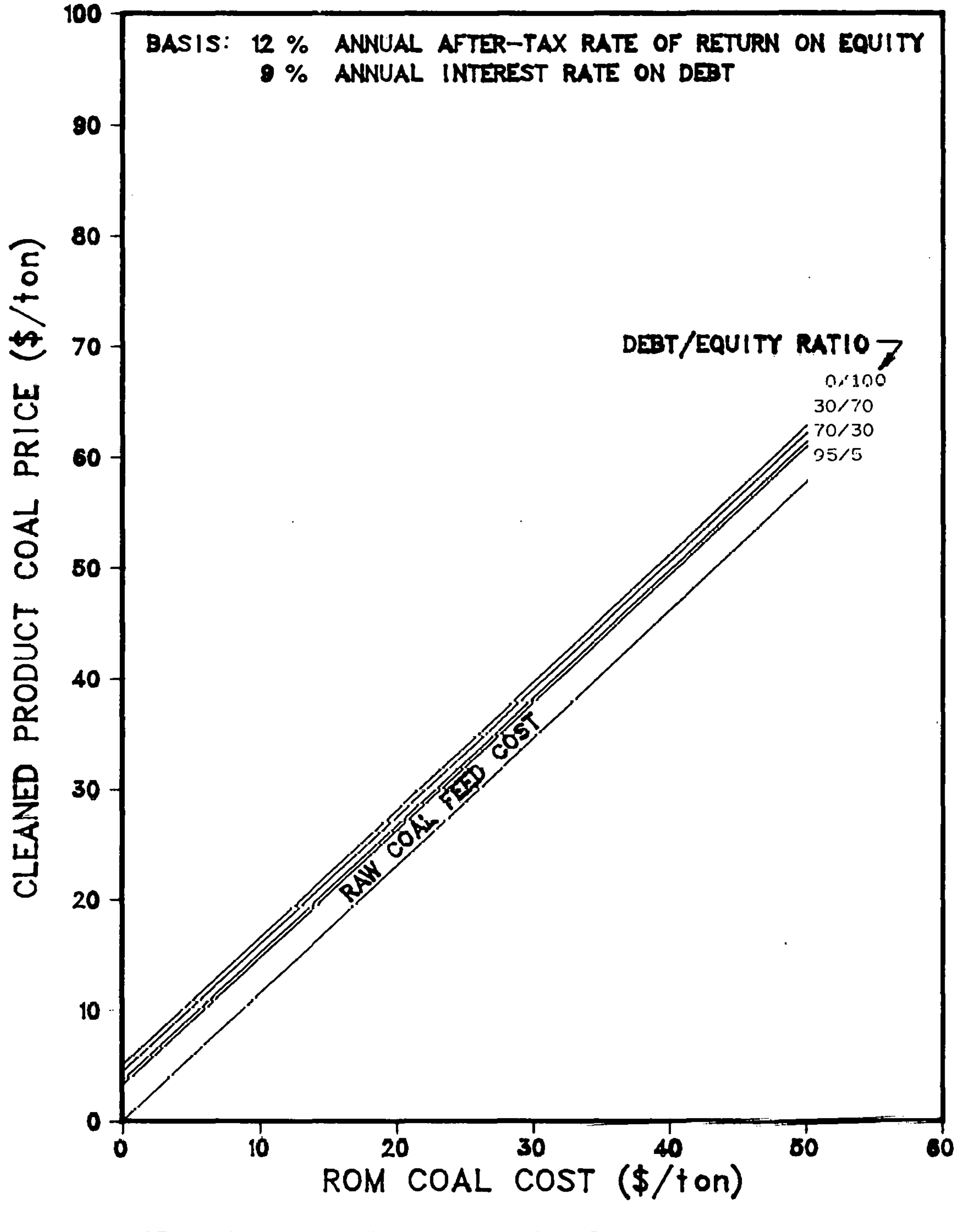


Fig. B-17. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

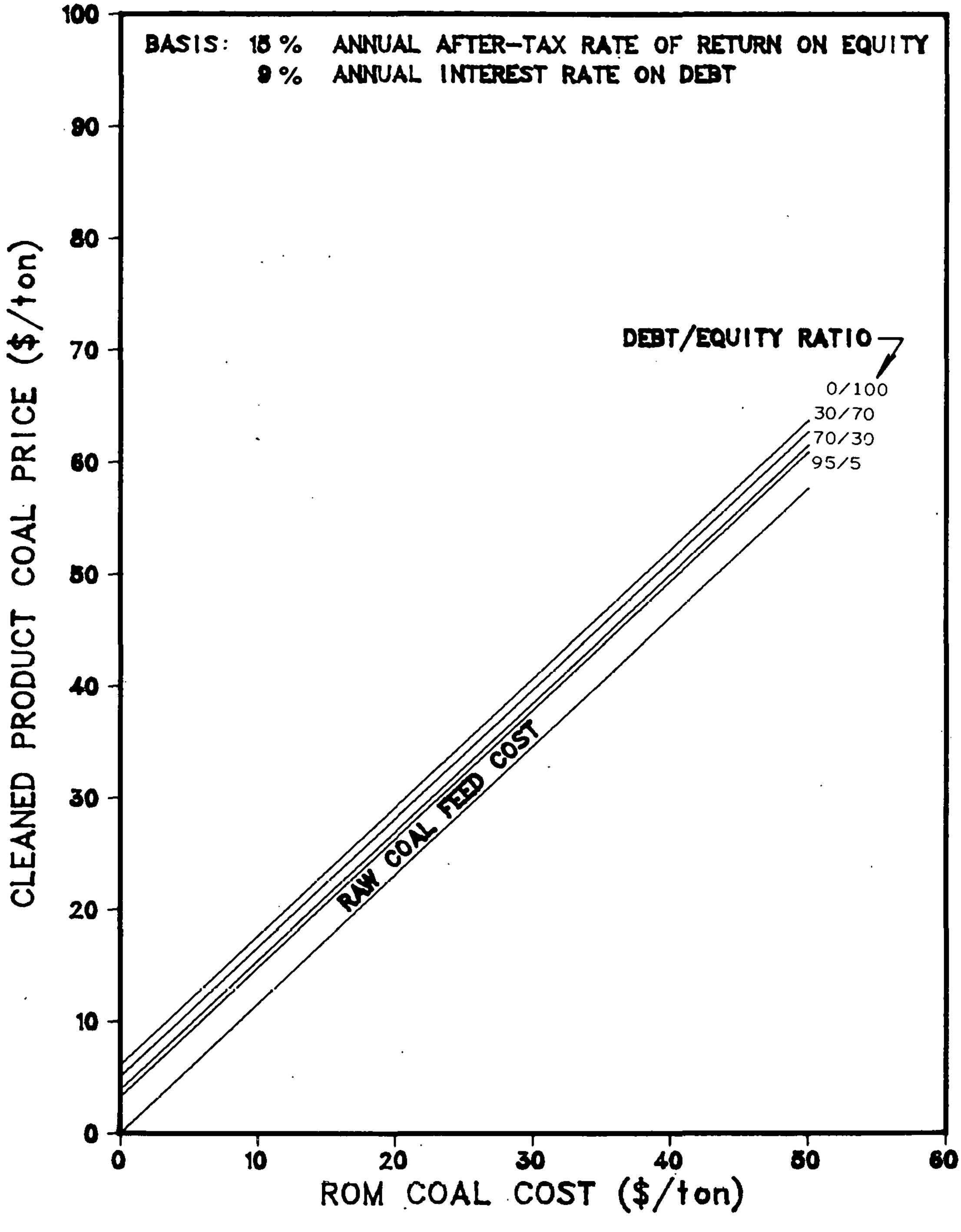


Fig. B-18. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

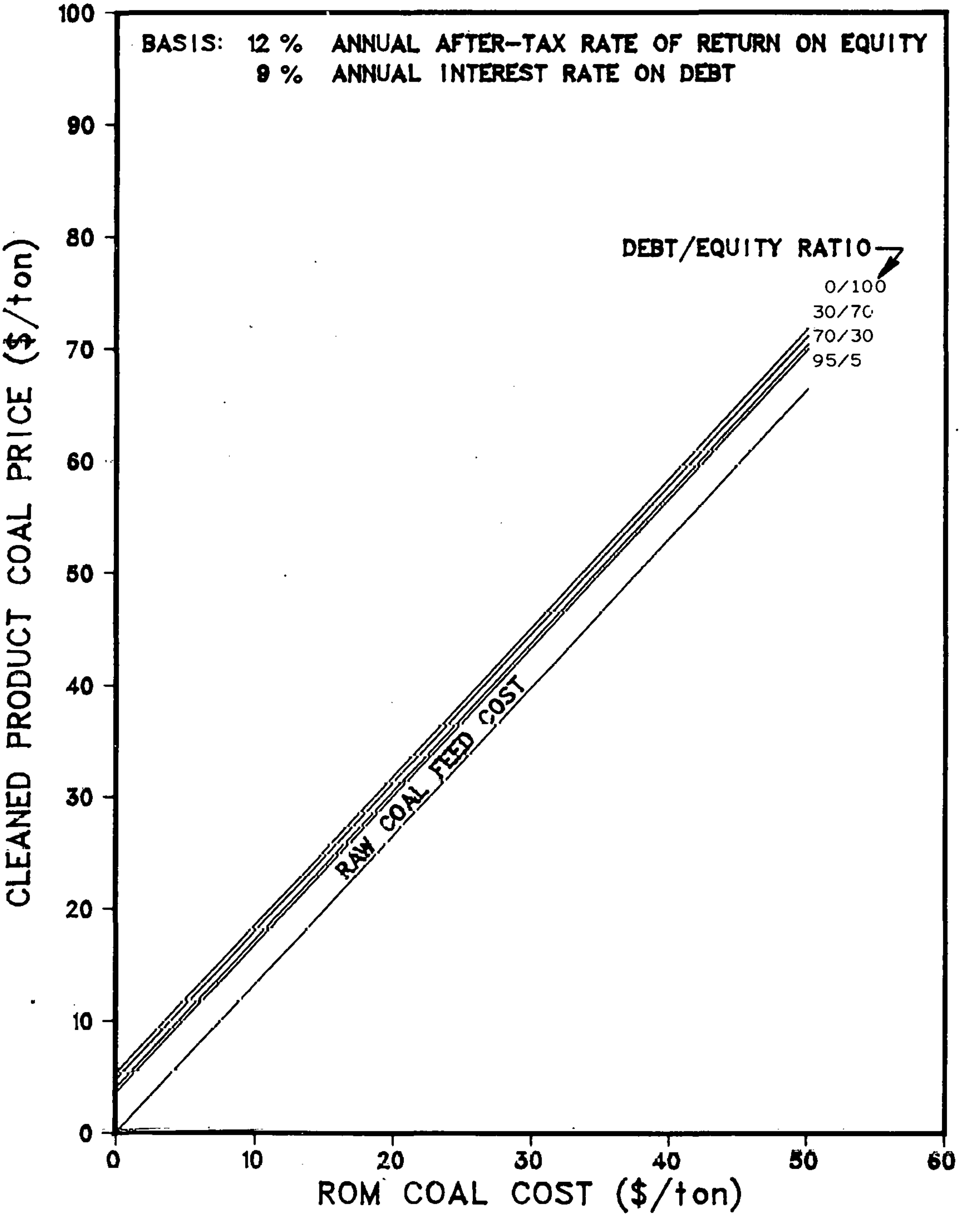


Fig. B-19. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

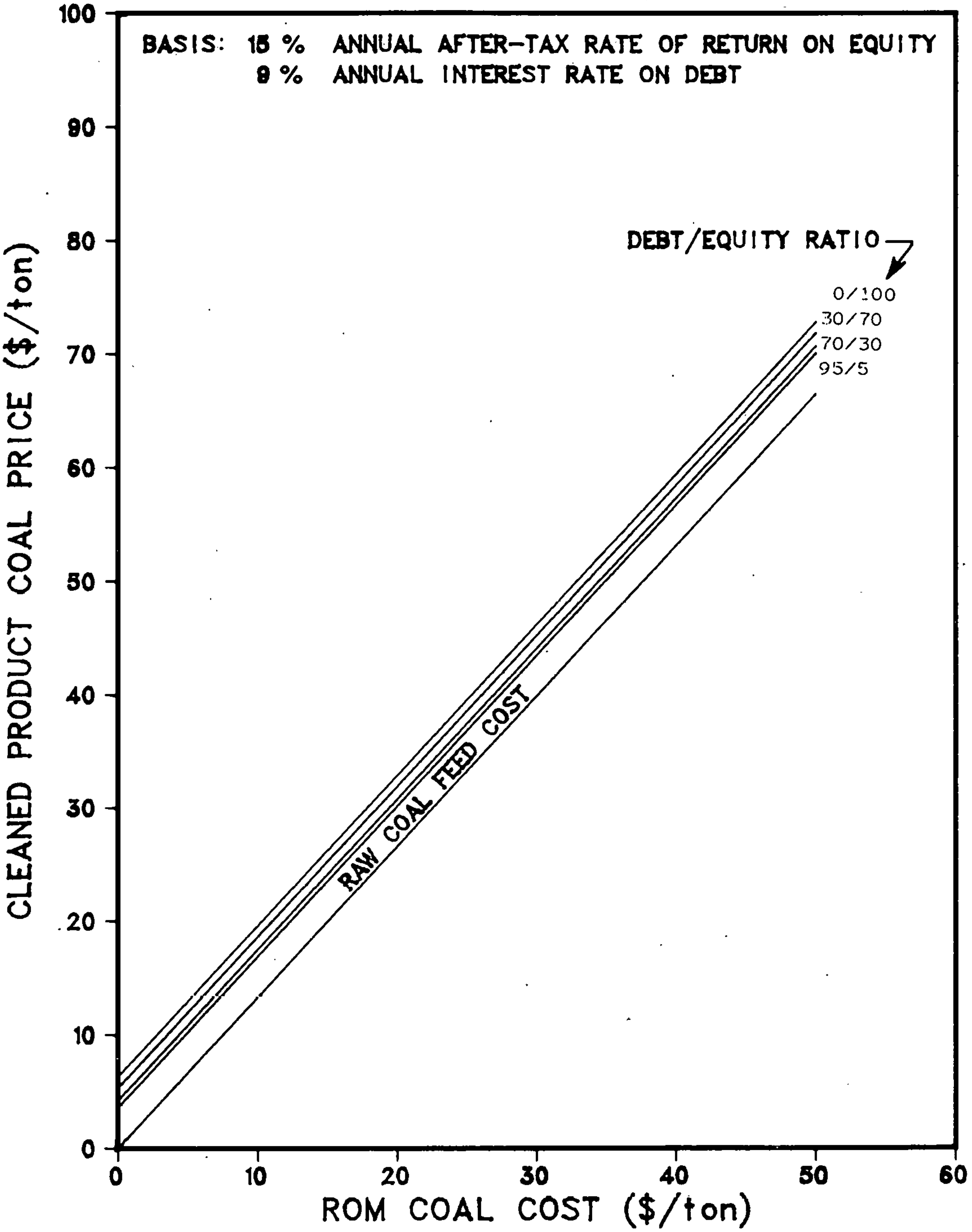


Fig. B-20. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

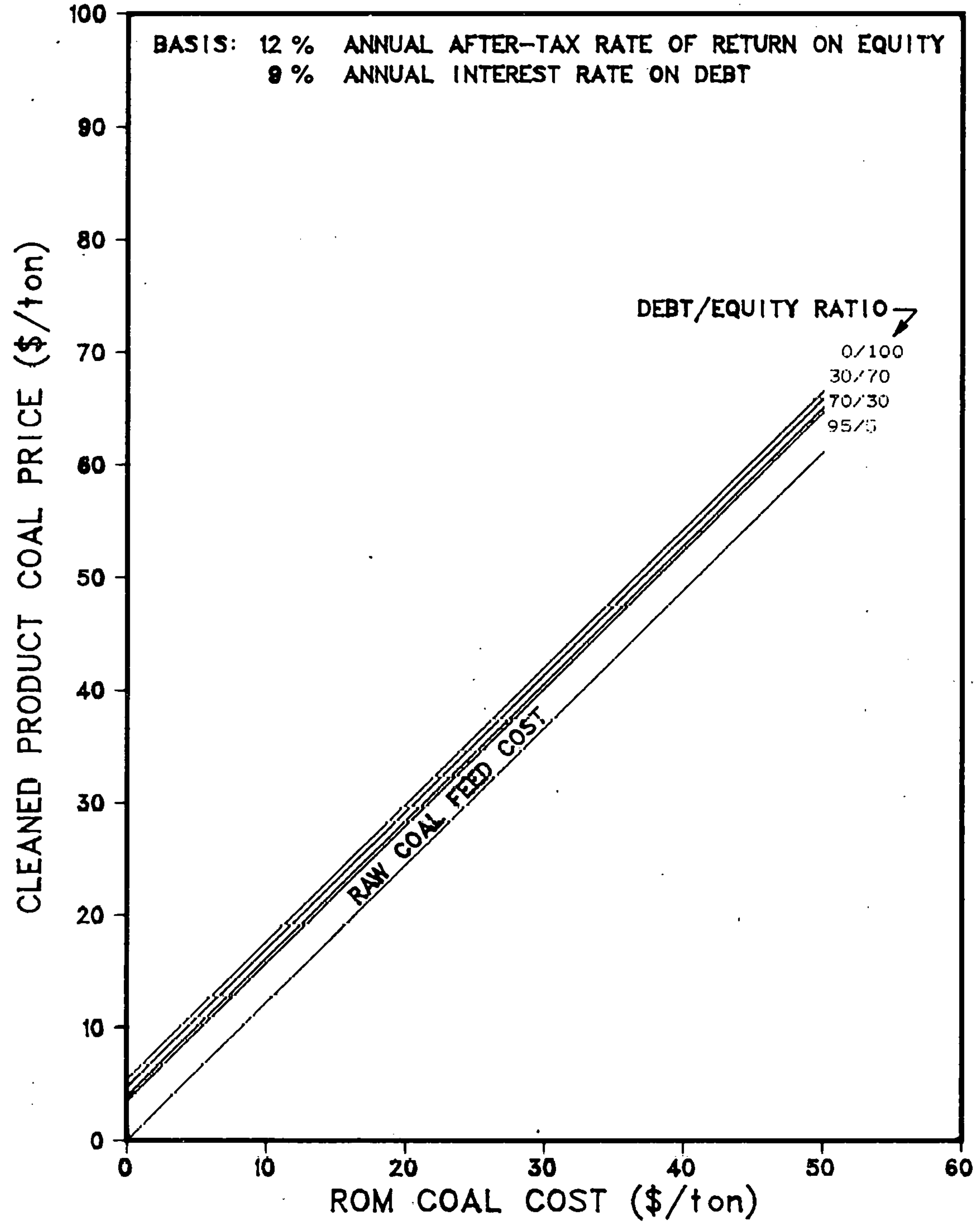


Fig. B-21. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

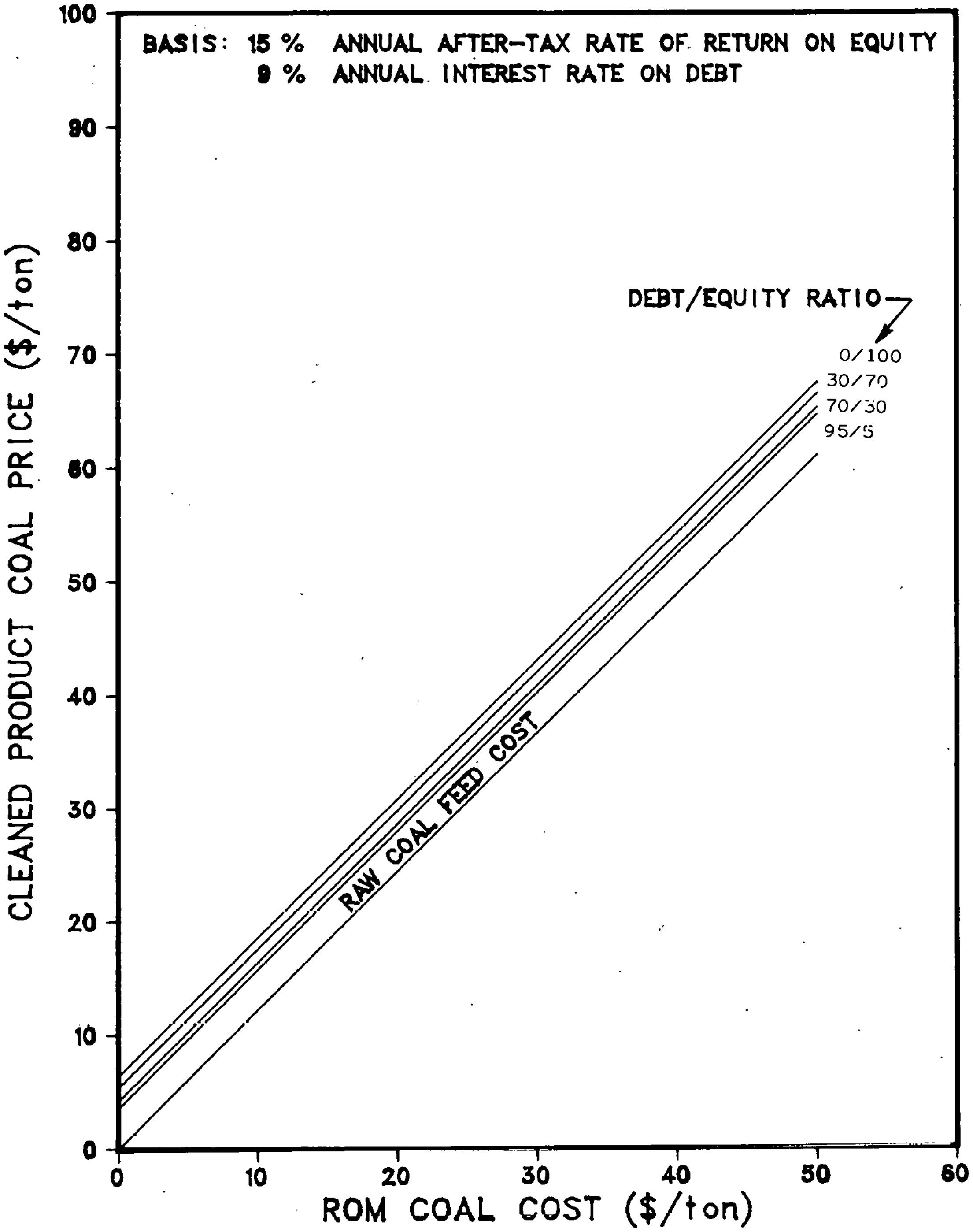


Fig. B-22. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

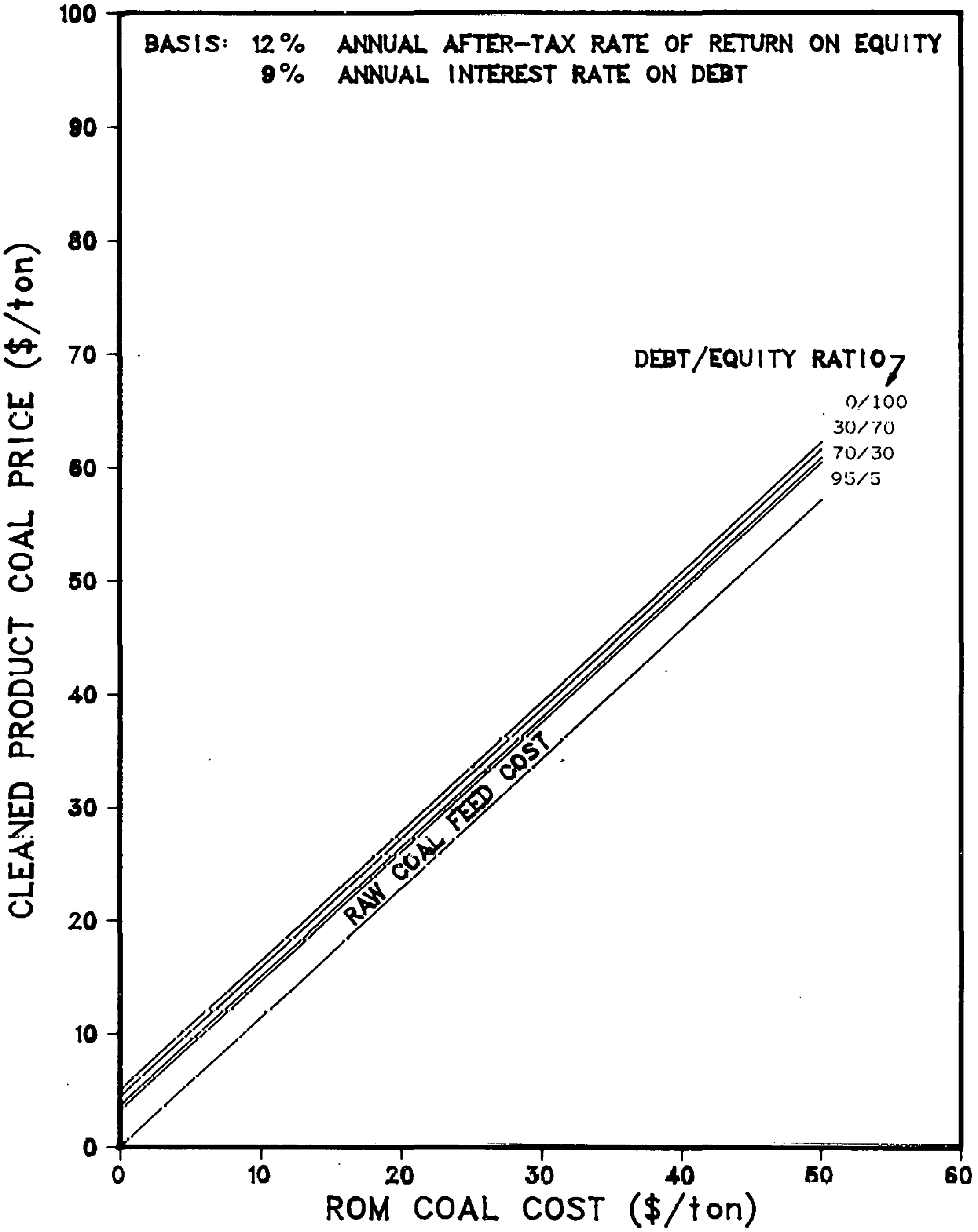


Fig. B-23. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

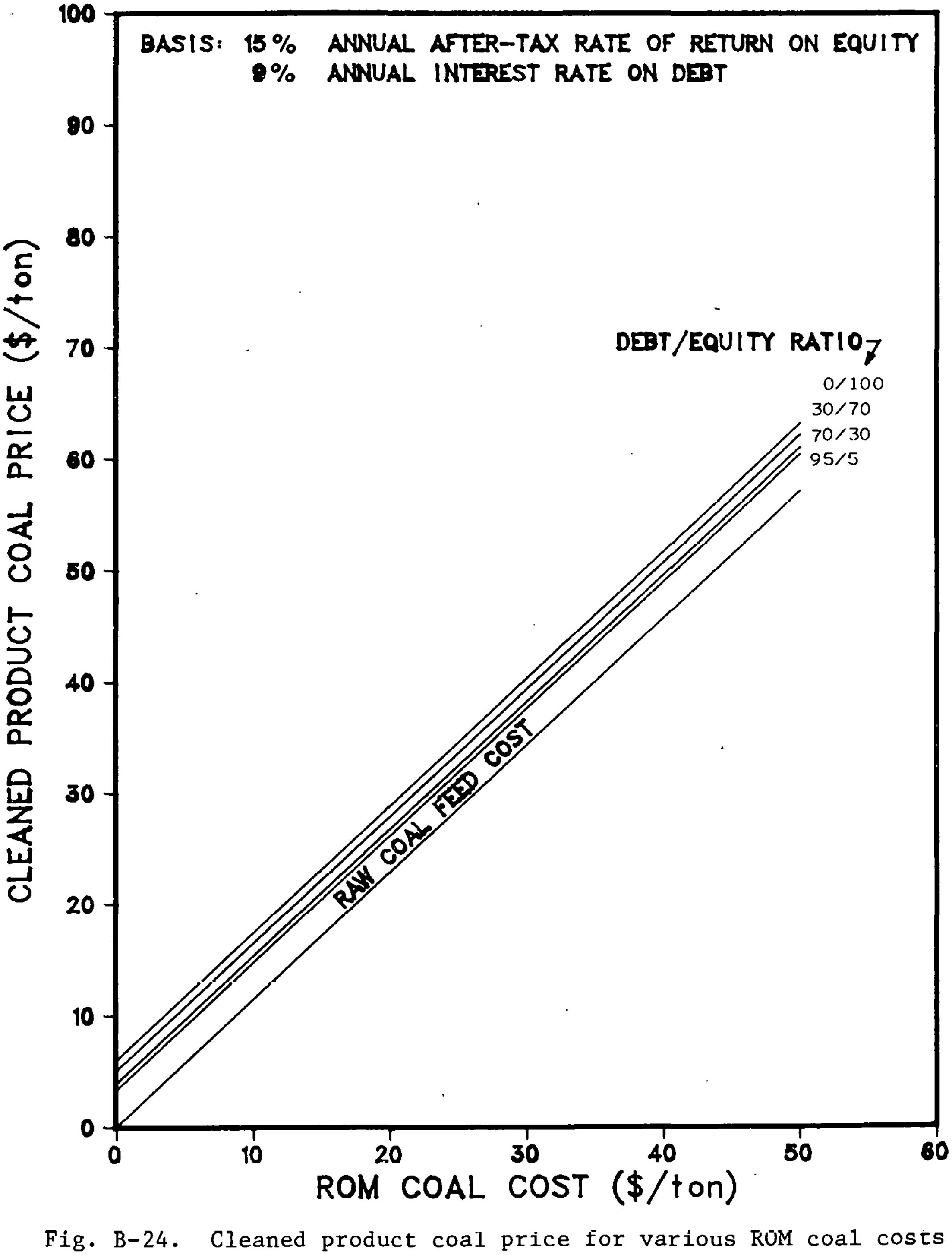


Fig. B-24. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: mild cleaning; 15,000 tons/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

B.2 Plots for Wet Mechanical Beneficiation — Deep-Cleaning Plants

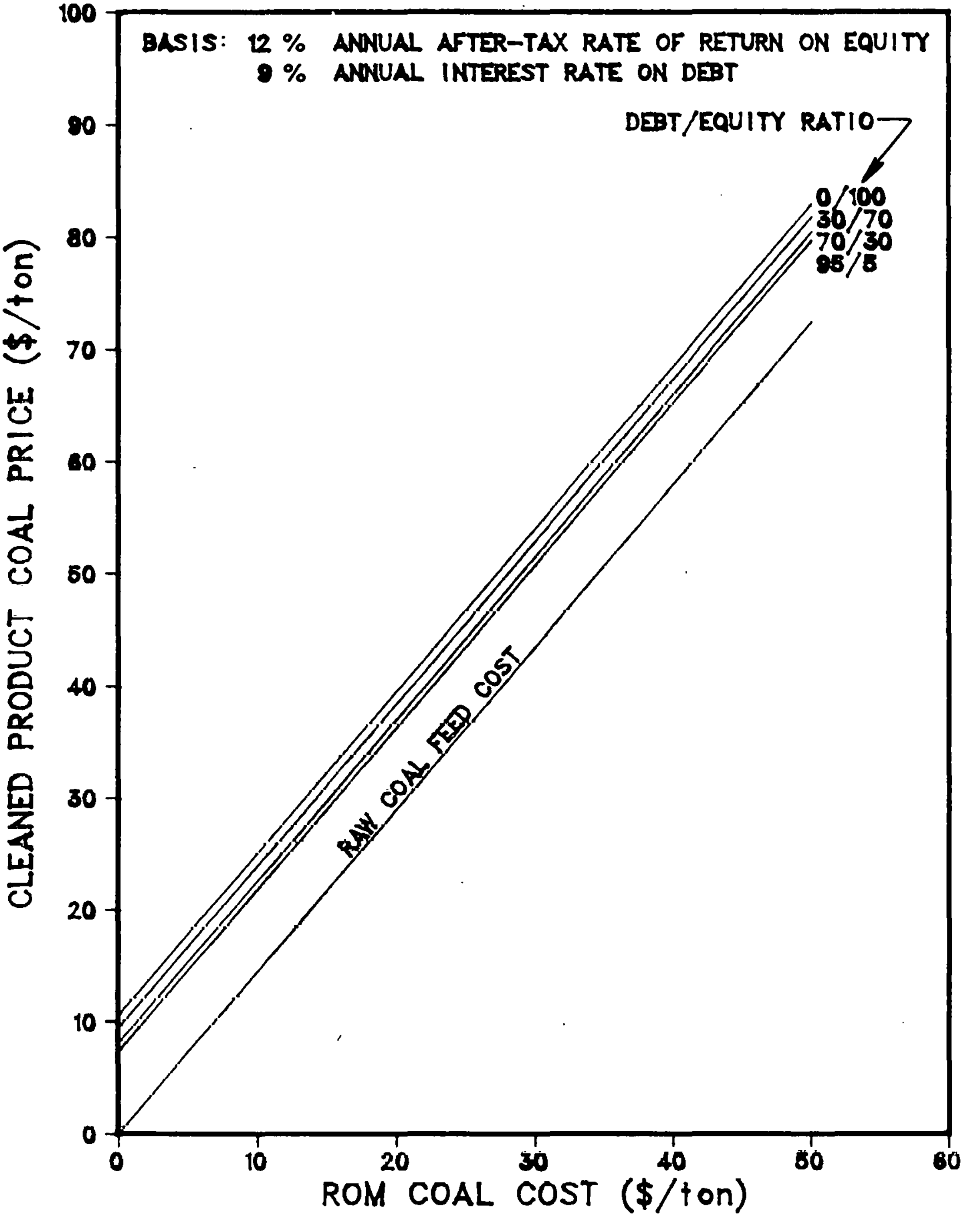


Fig. B-25. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

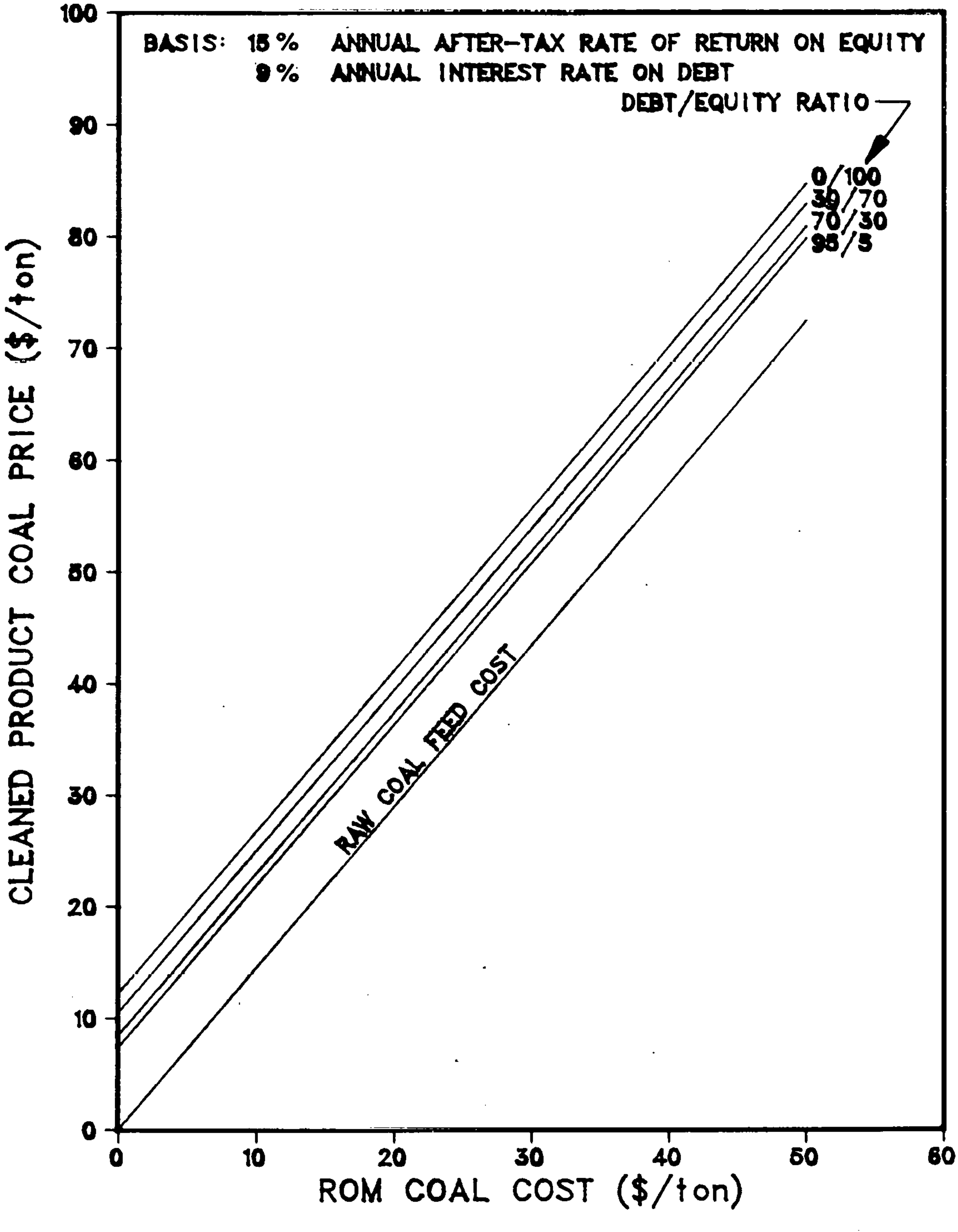


Fig. B-26. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

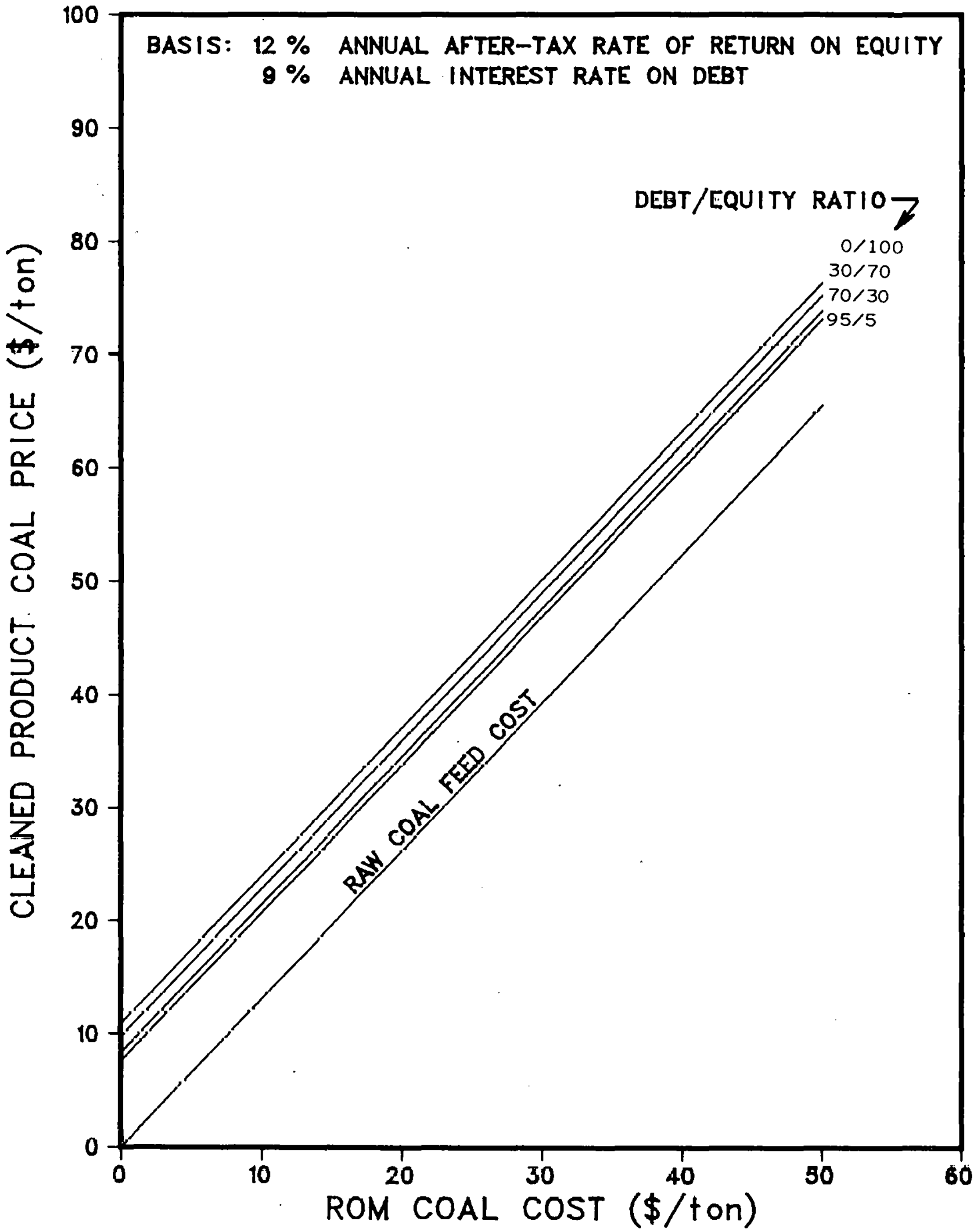


Fig. B-27. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

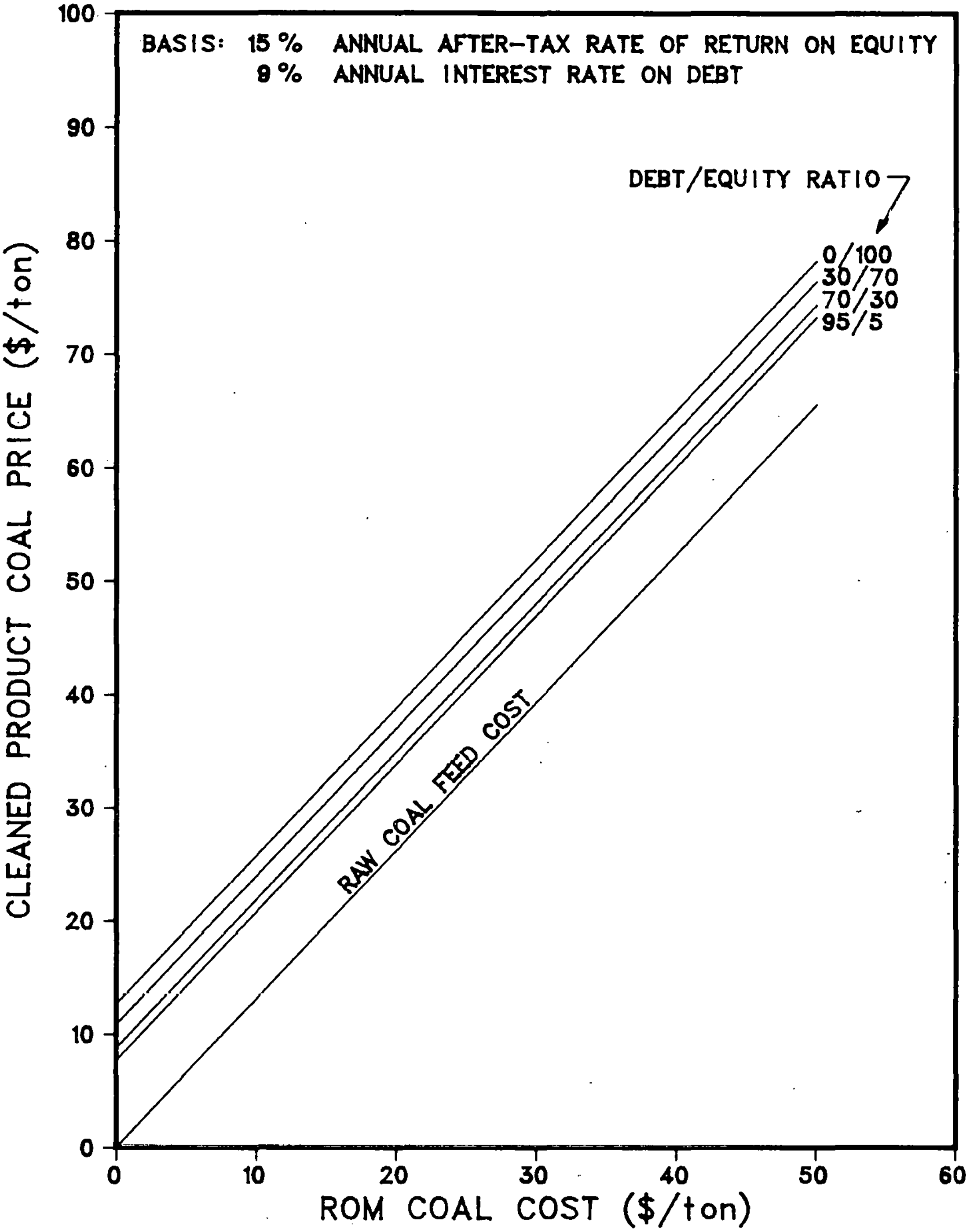


Fig. B-28. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

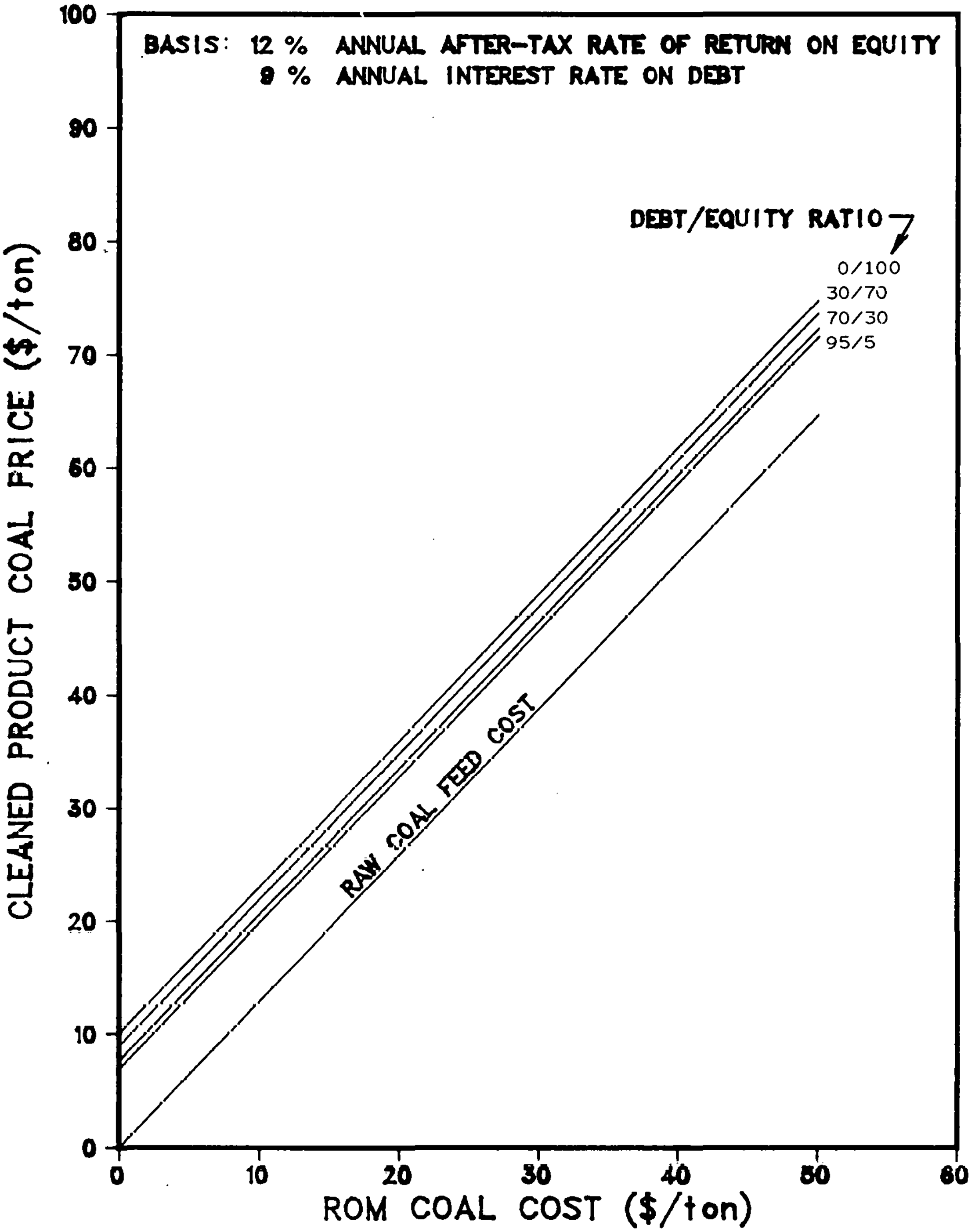


Fig. B-29. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

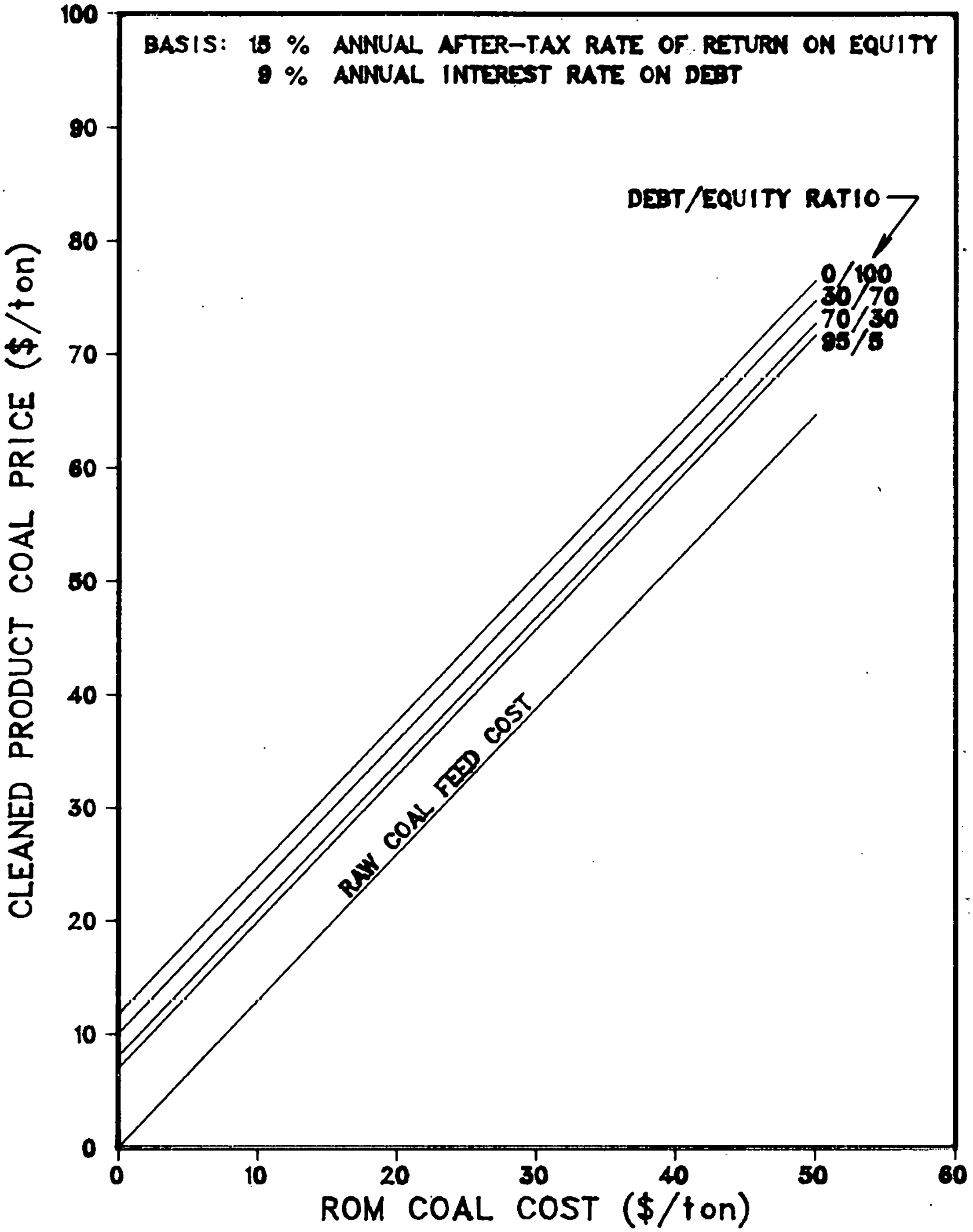


Fig. B-30. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

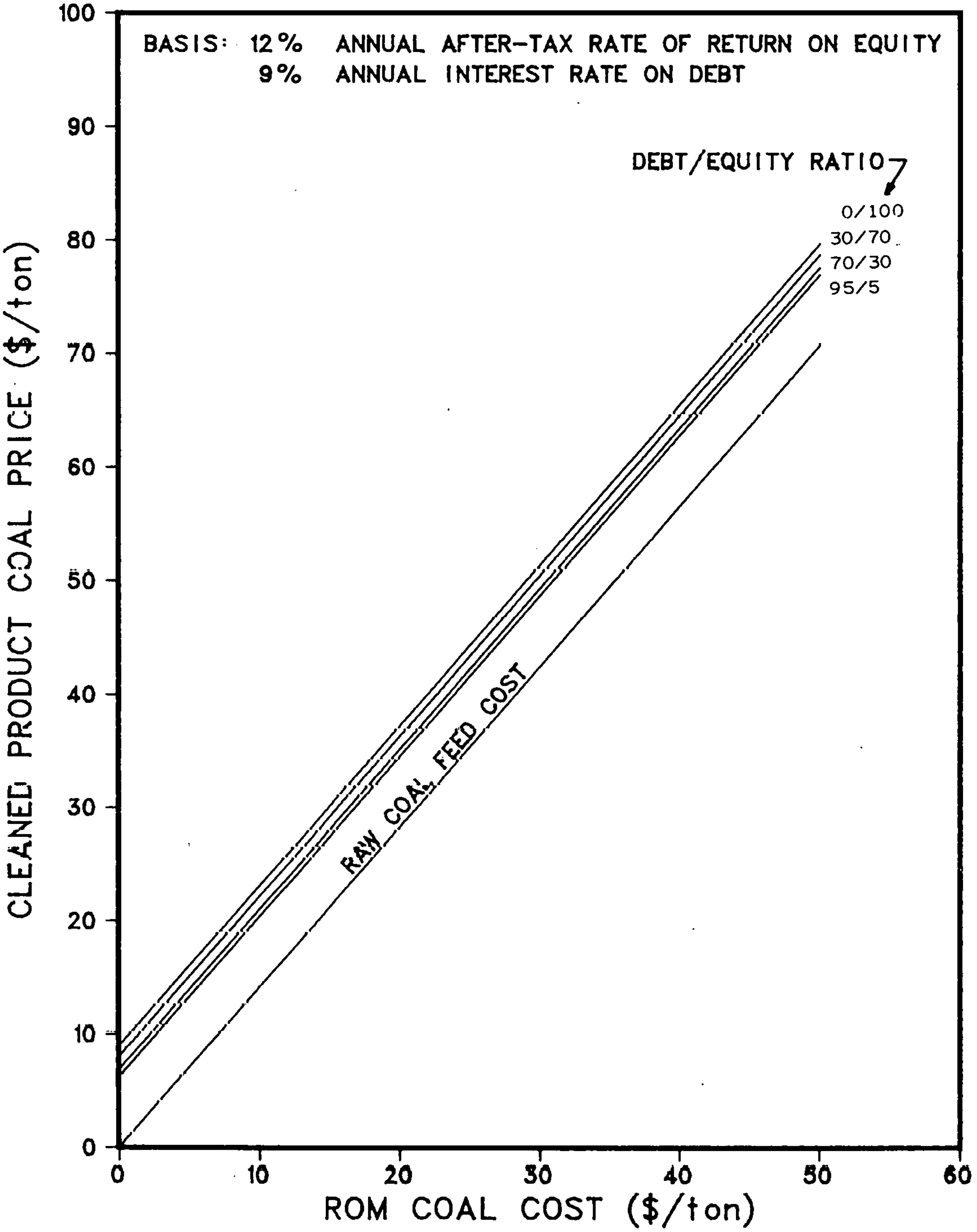


Fig. B-31. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

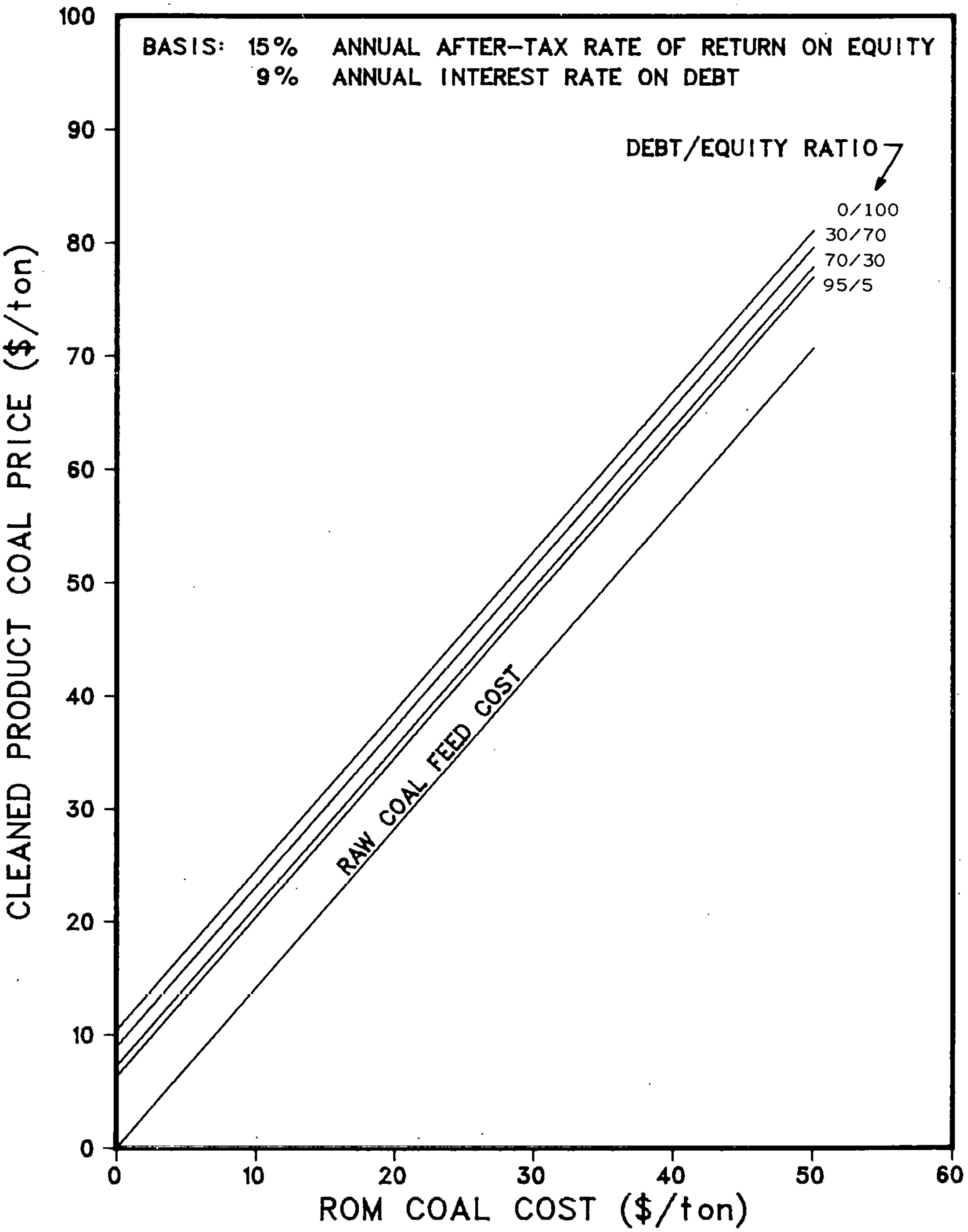


Fig. B-32. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

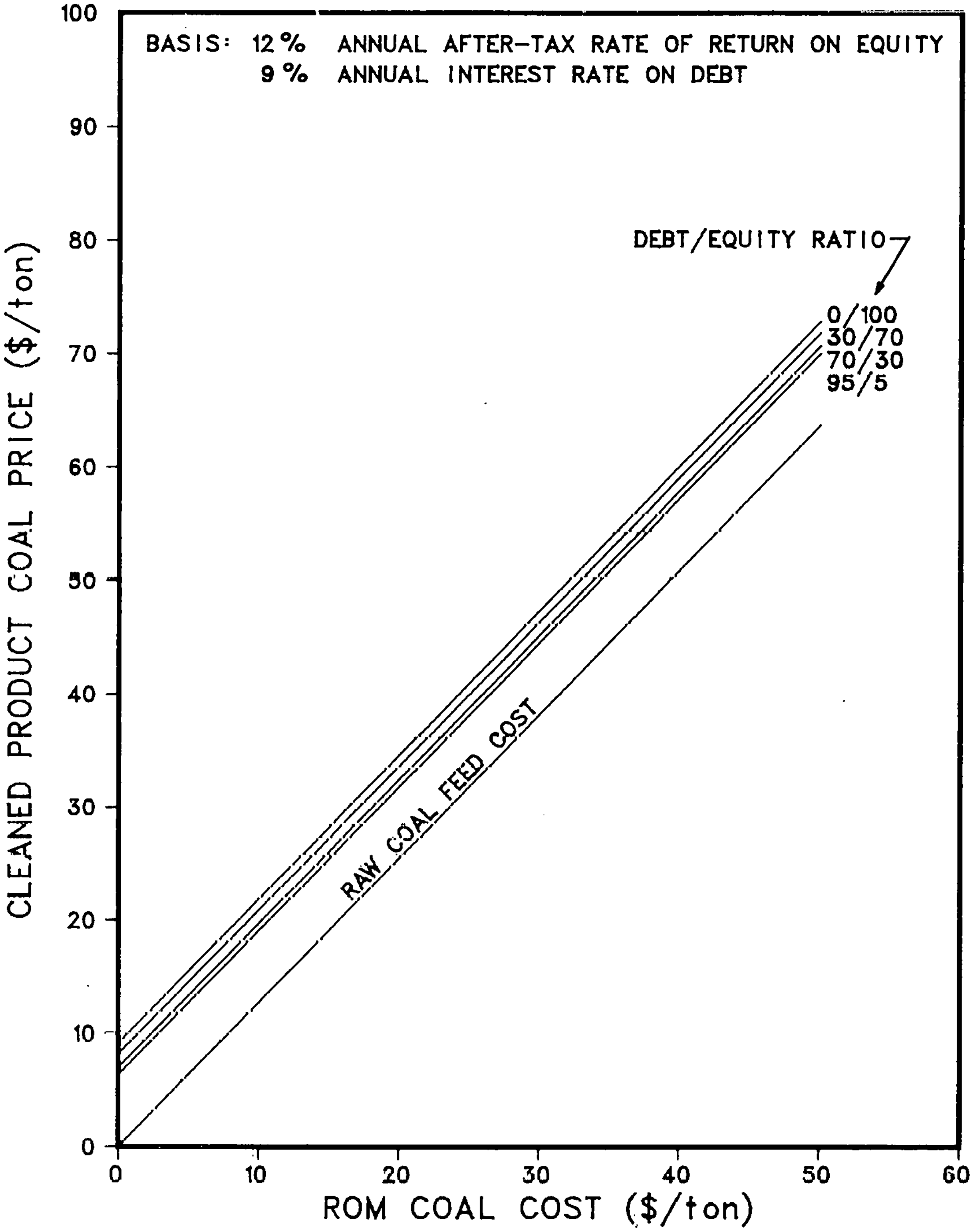


Fig. B-33. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

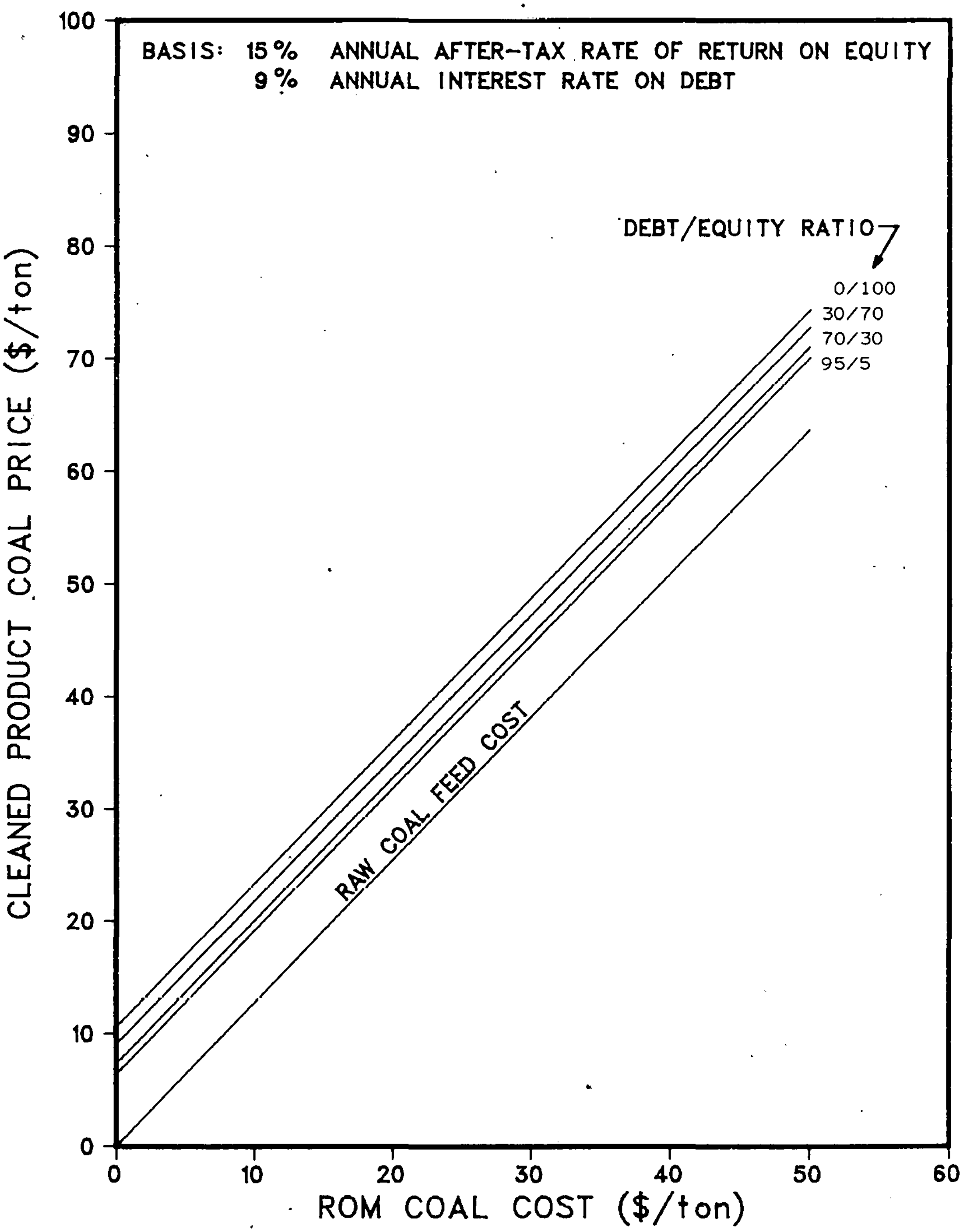


Fig. B-34. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

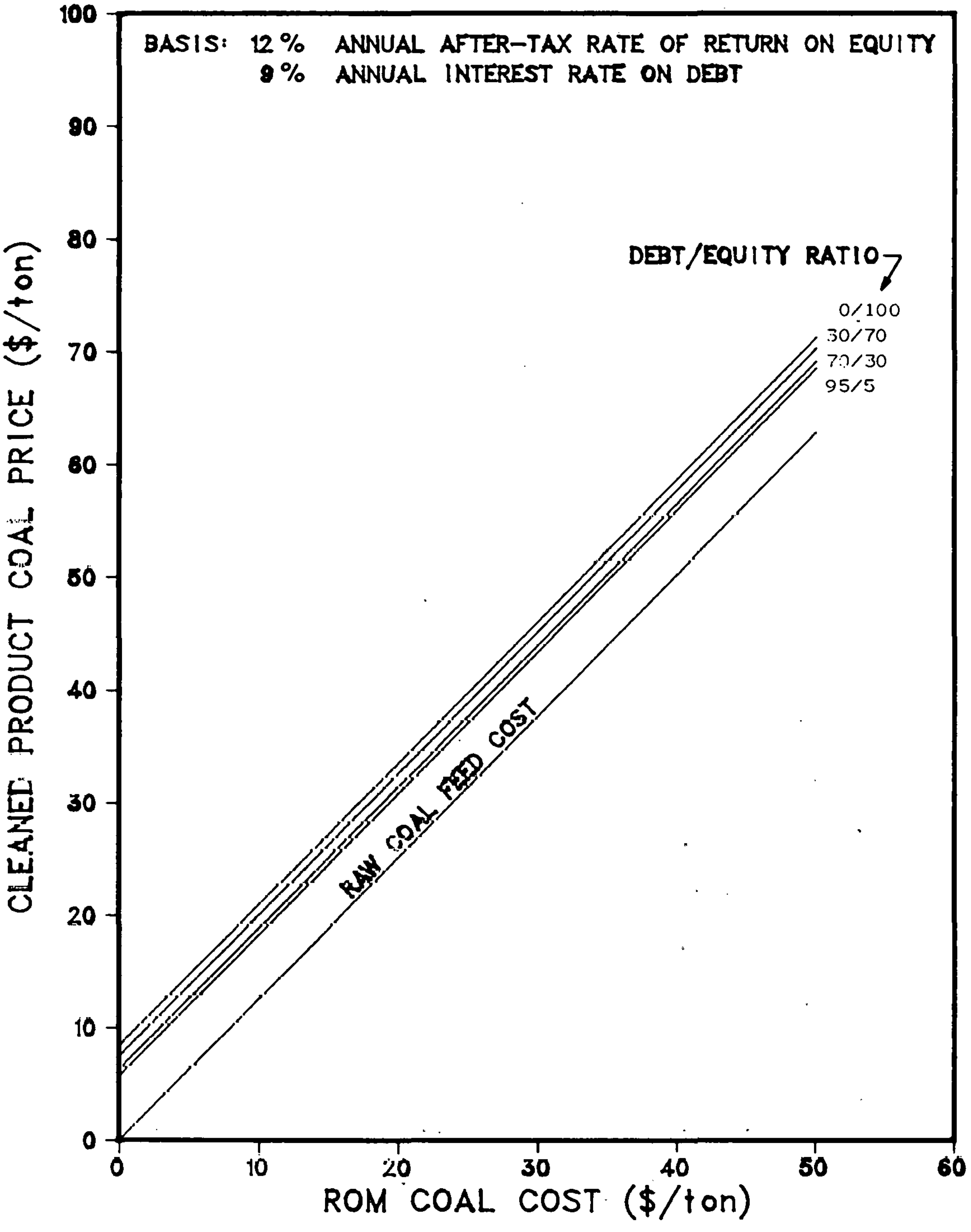


Fig. B-35. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

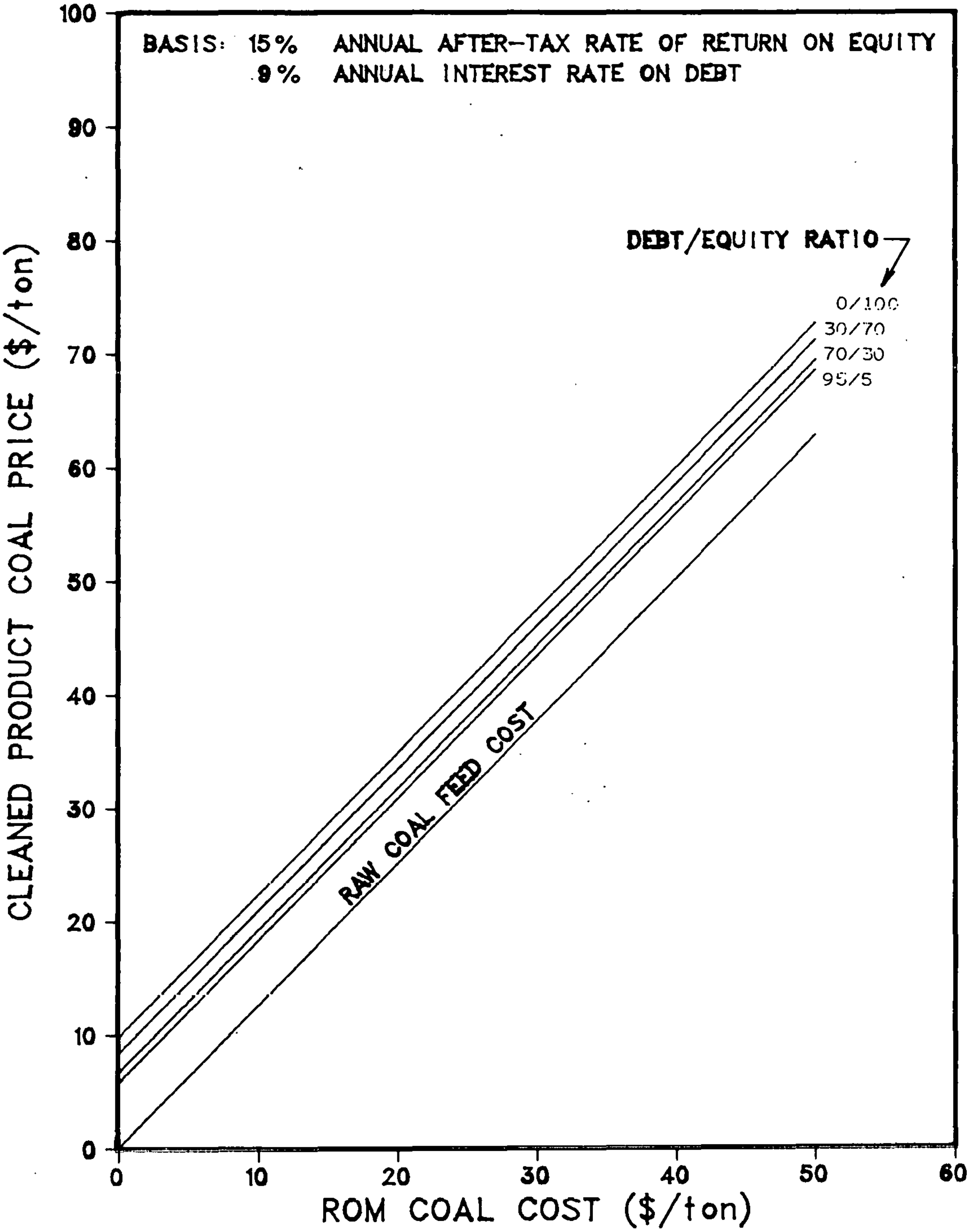


Fig. B-36. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 1500-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

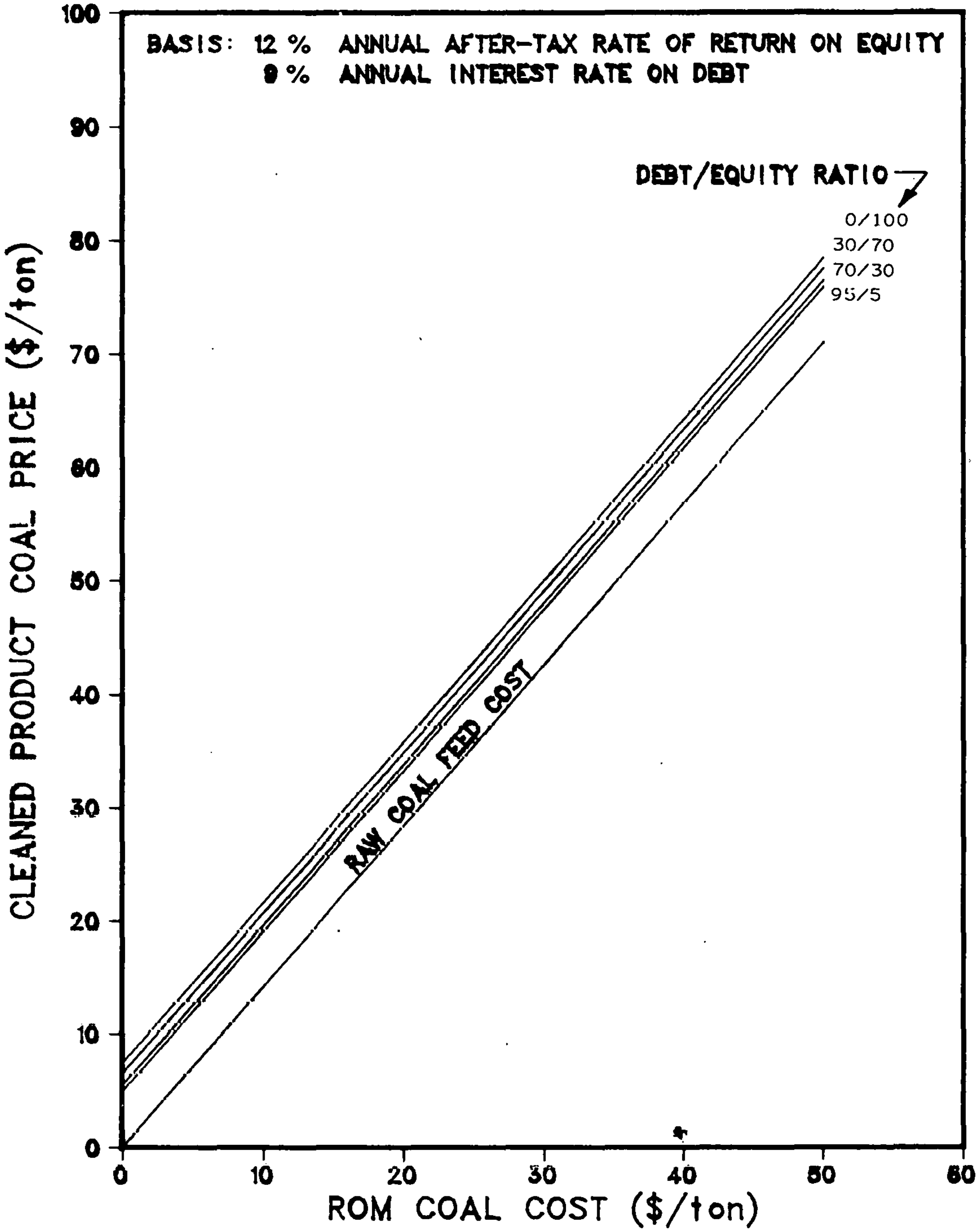


Fig. B-37. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

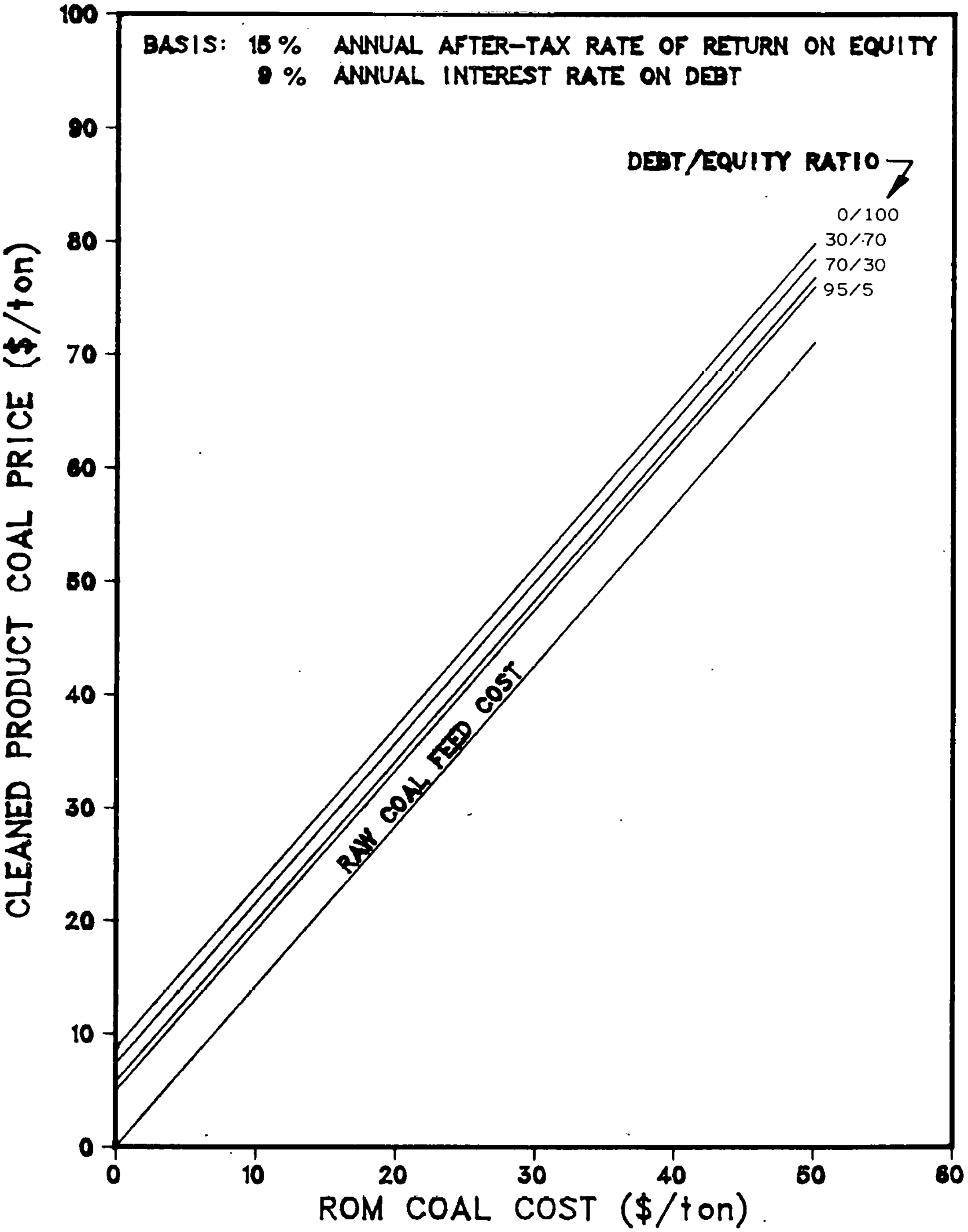


Fig. B-38. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

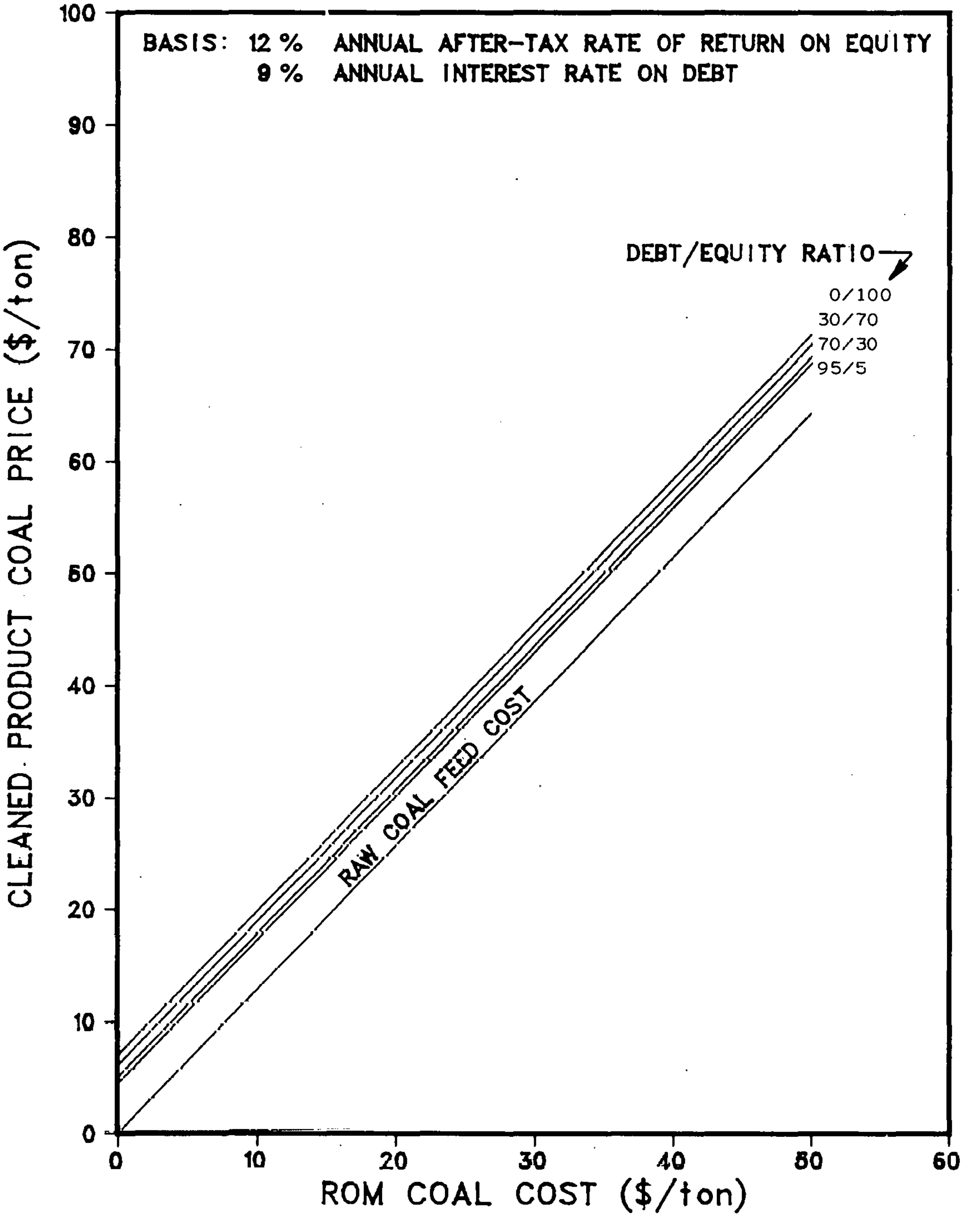


Fig. B-39. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

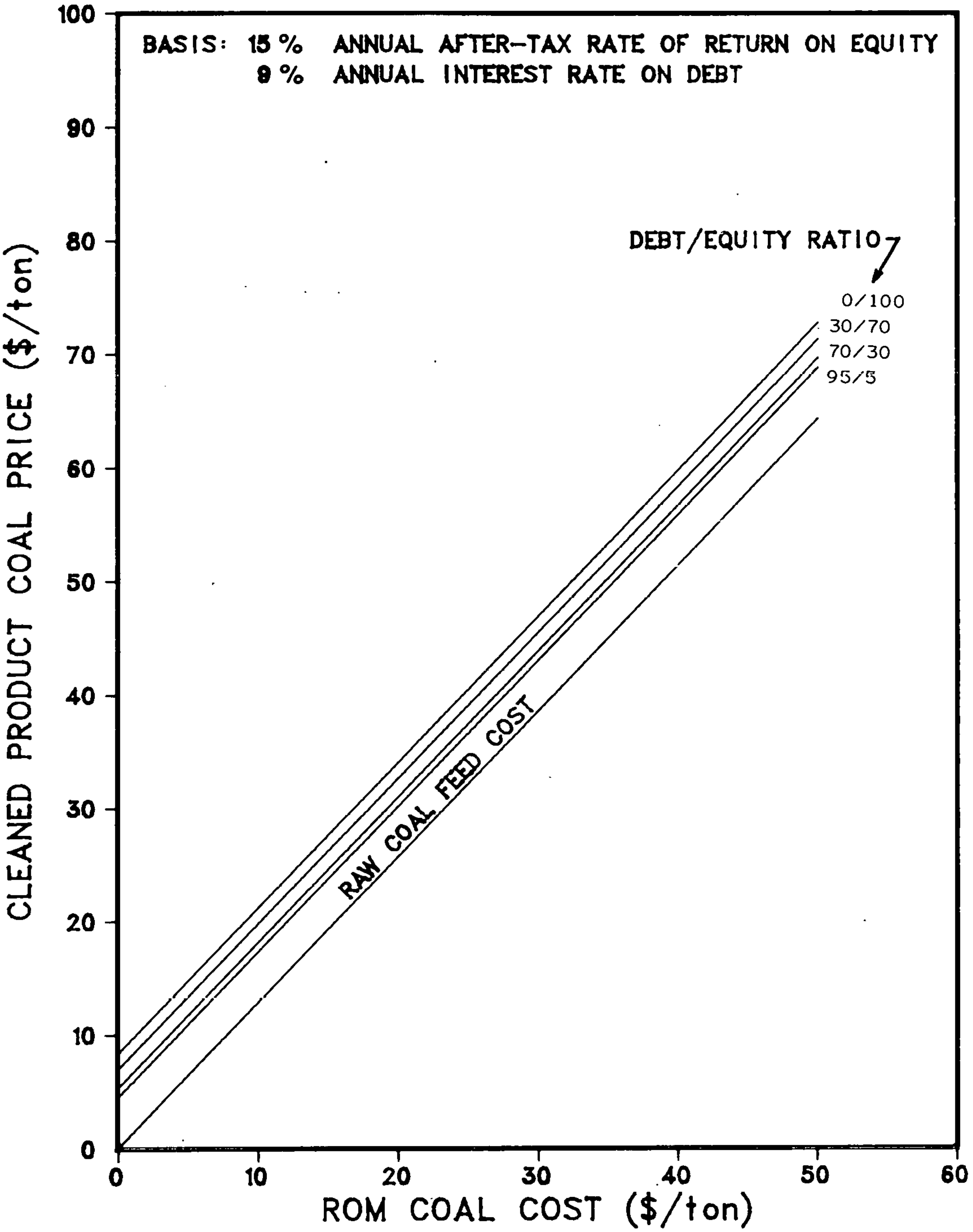


Fig. B-40. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

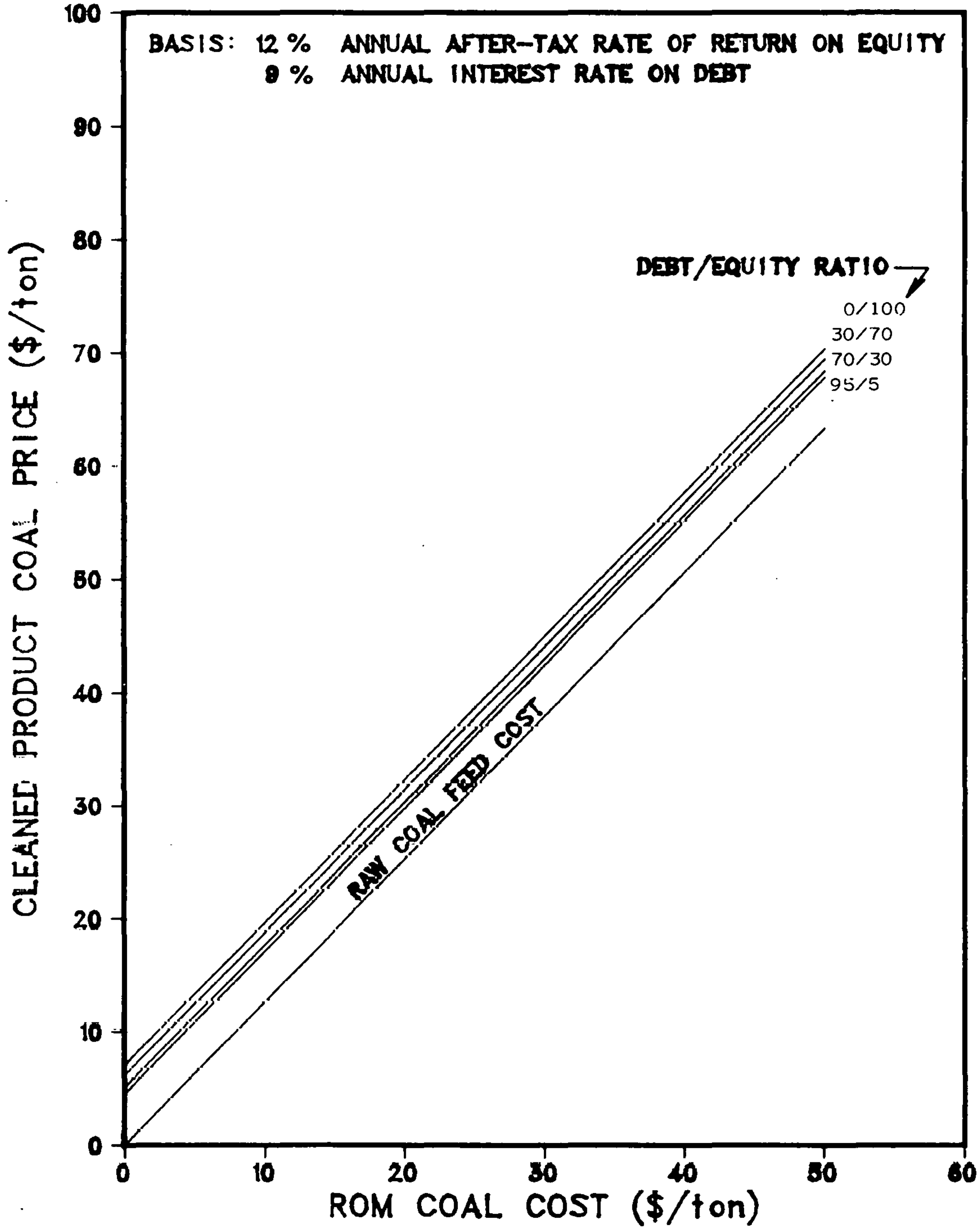


Fig. B-41. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

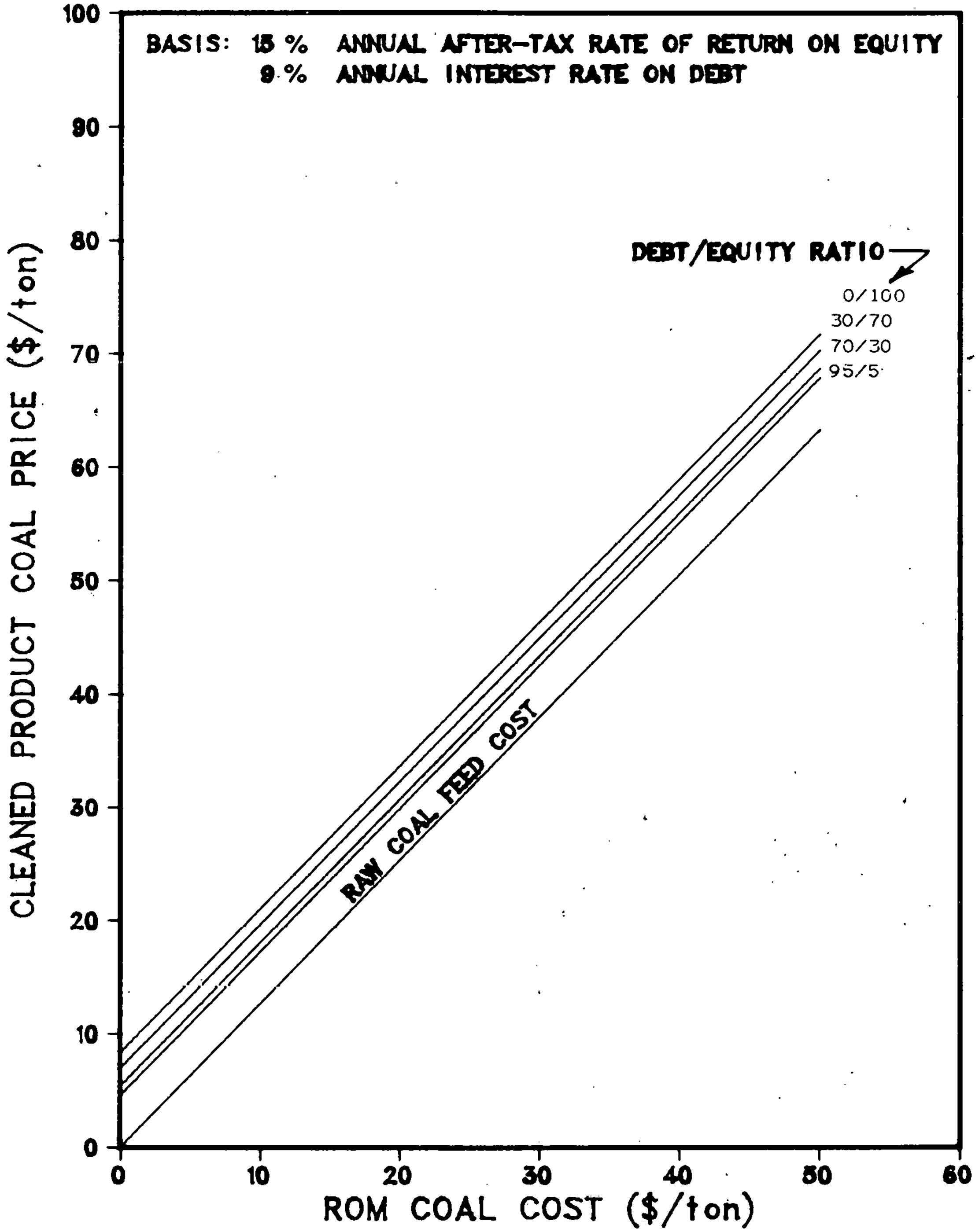


Fig. B-42. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

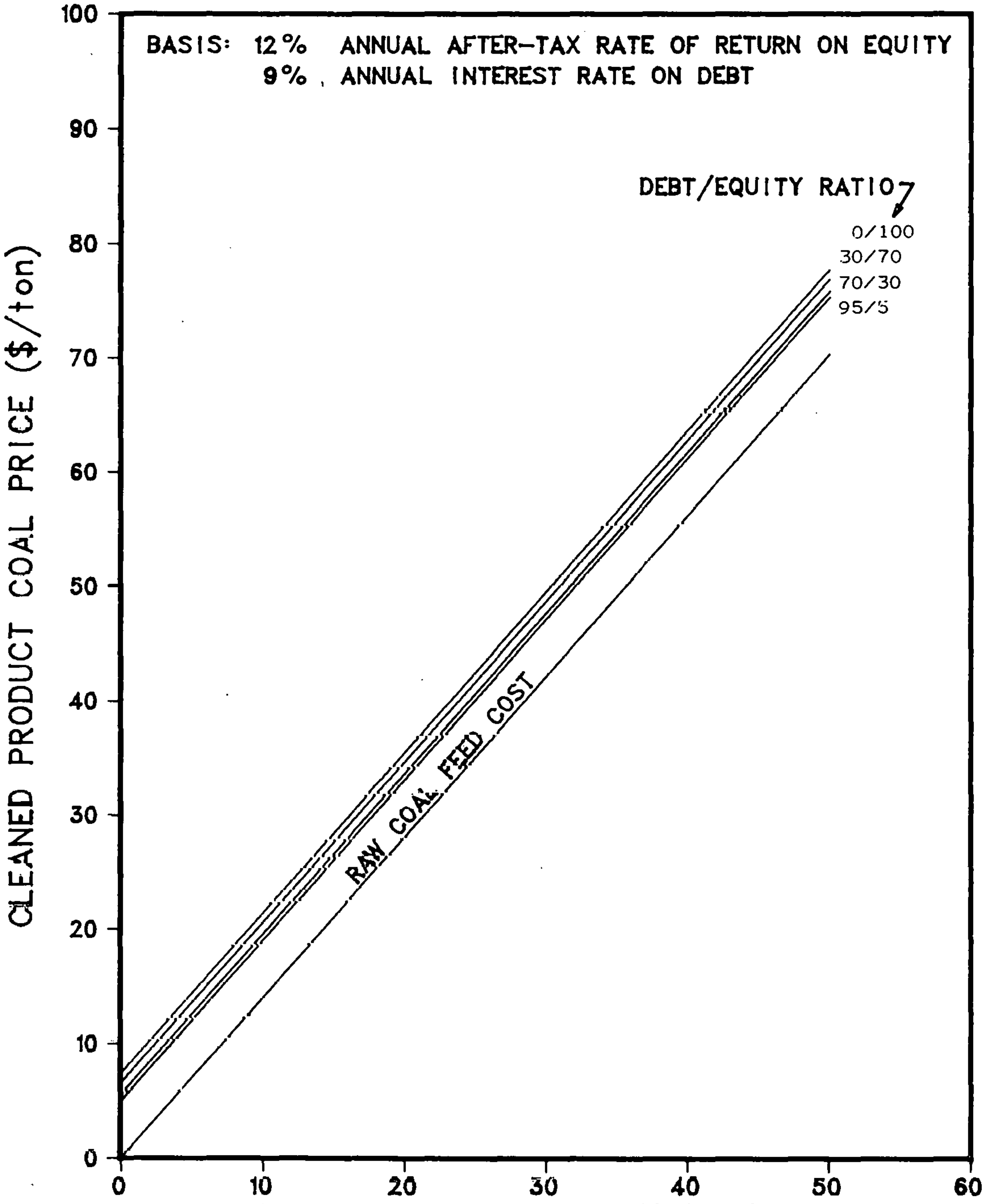


Fig. B-43. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

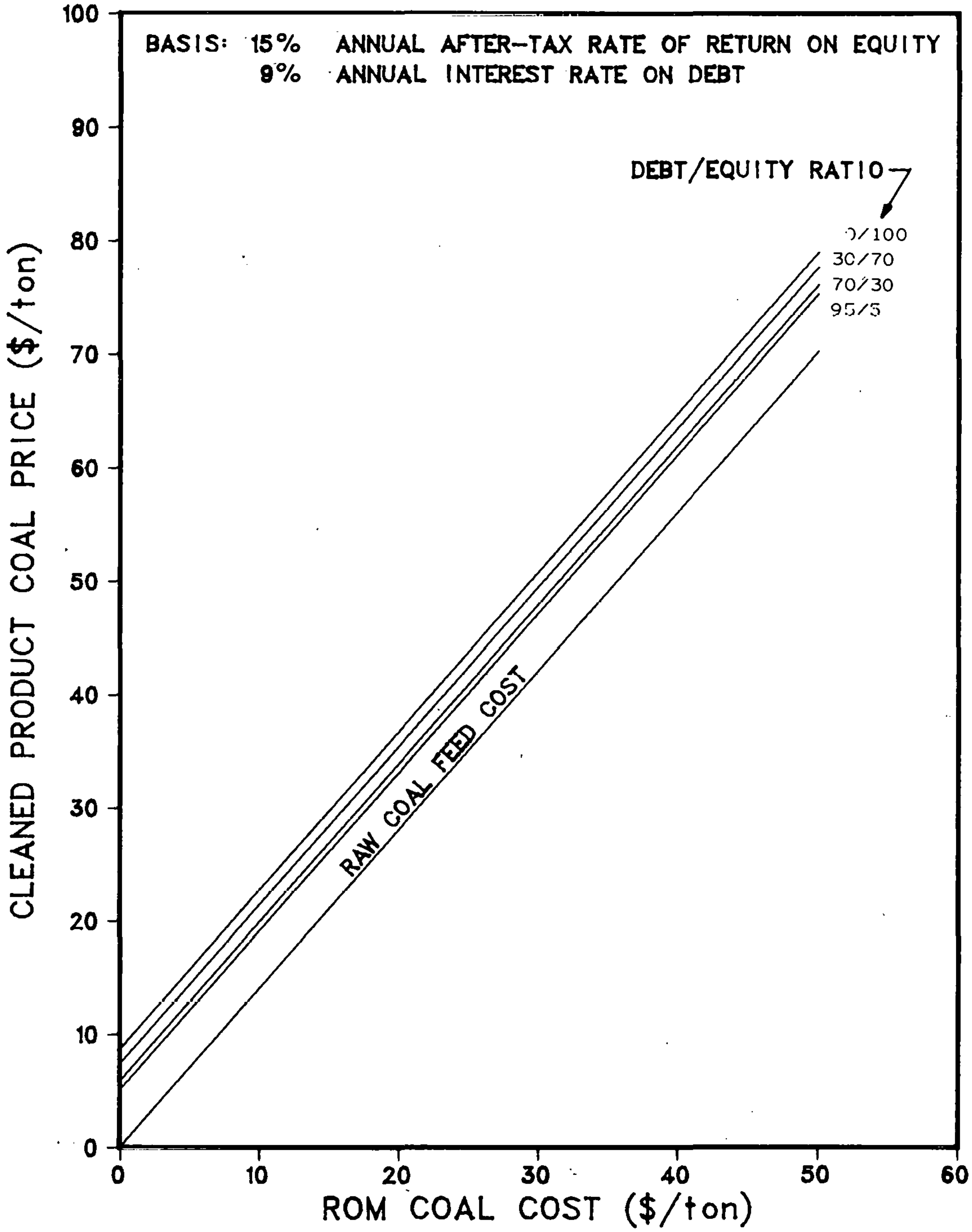


Fig. B-44. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

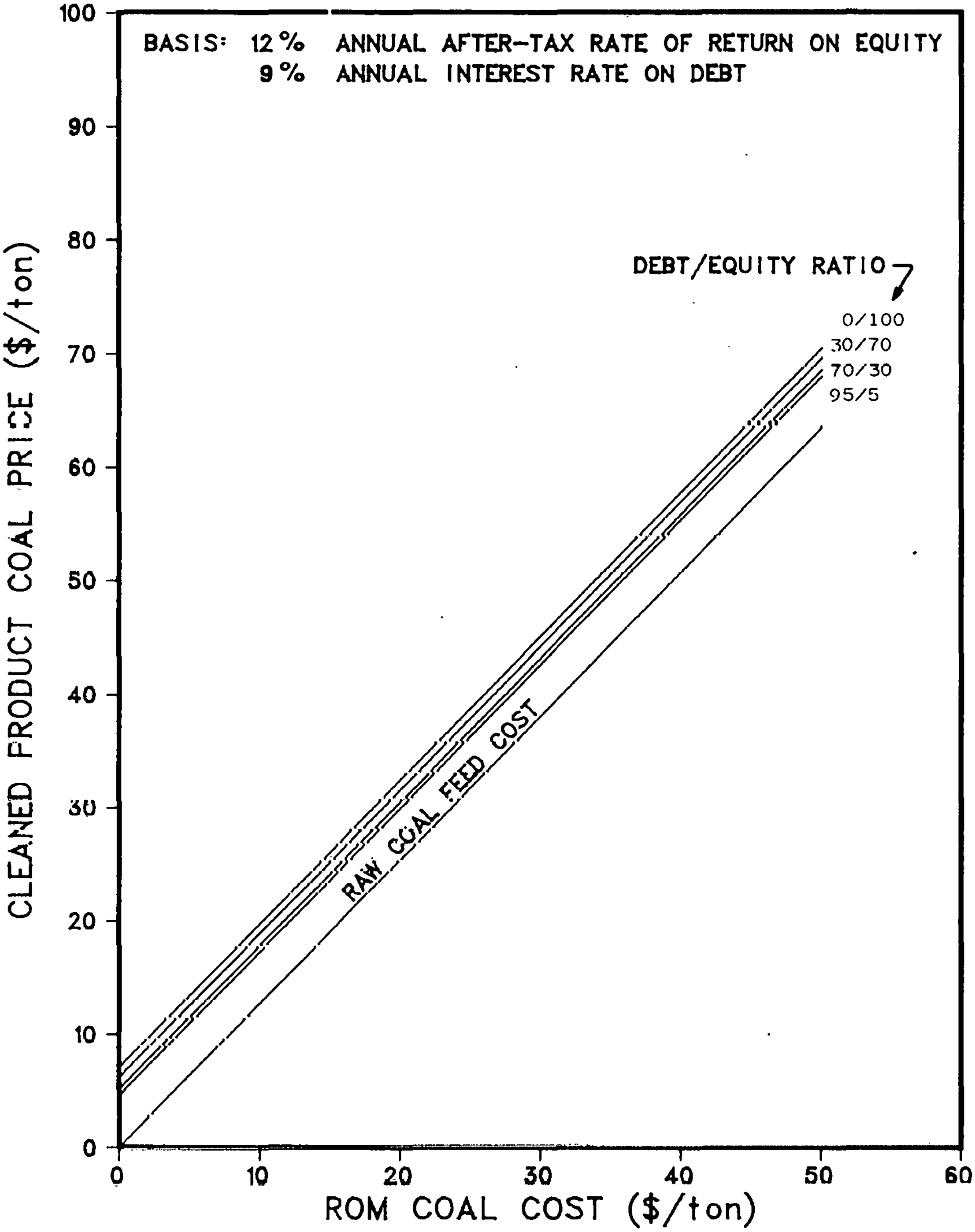


Fig. B-45. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

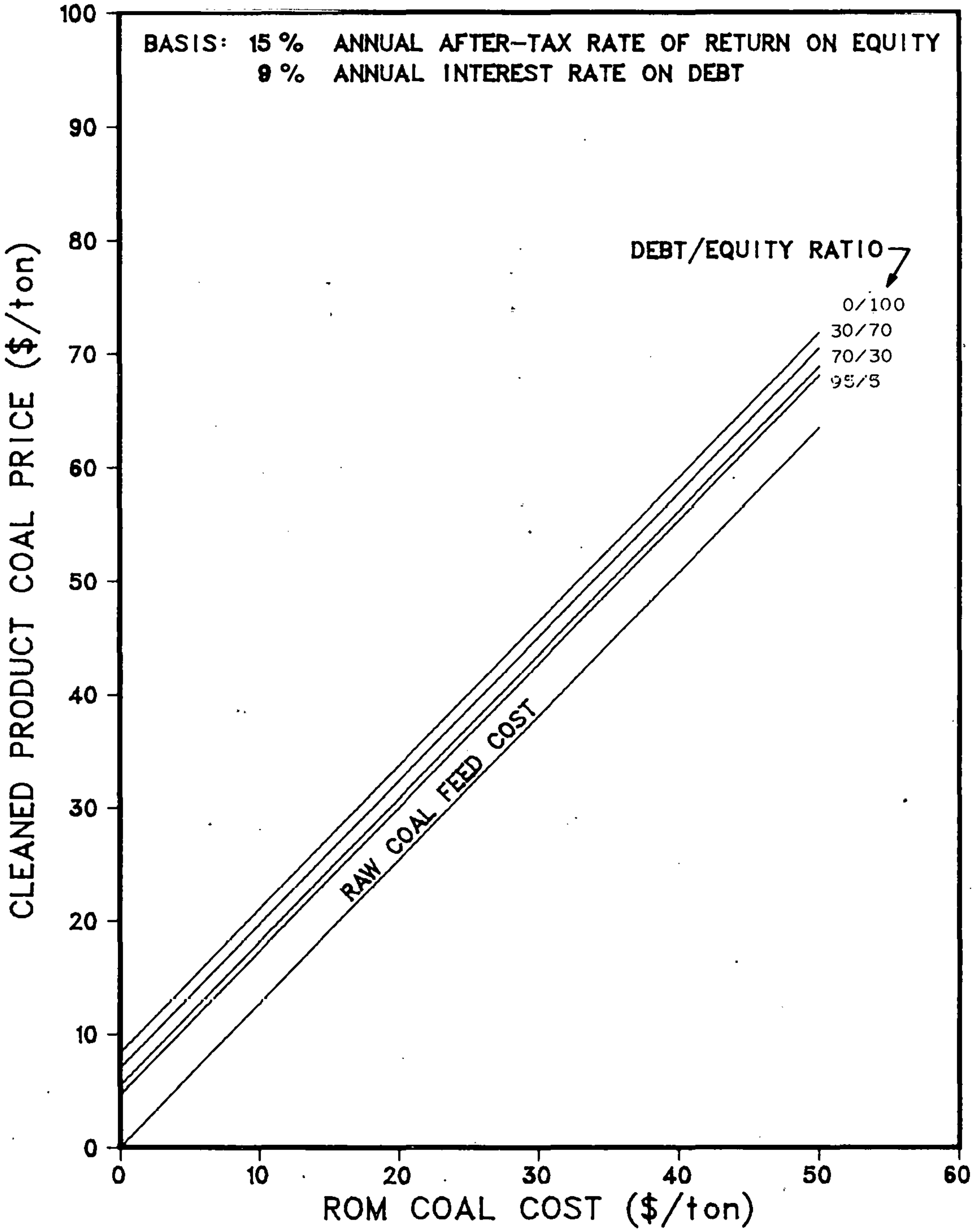


Fig. B-46. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

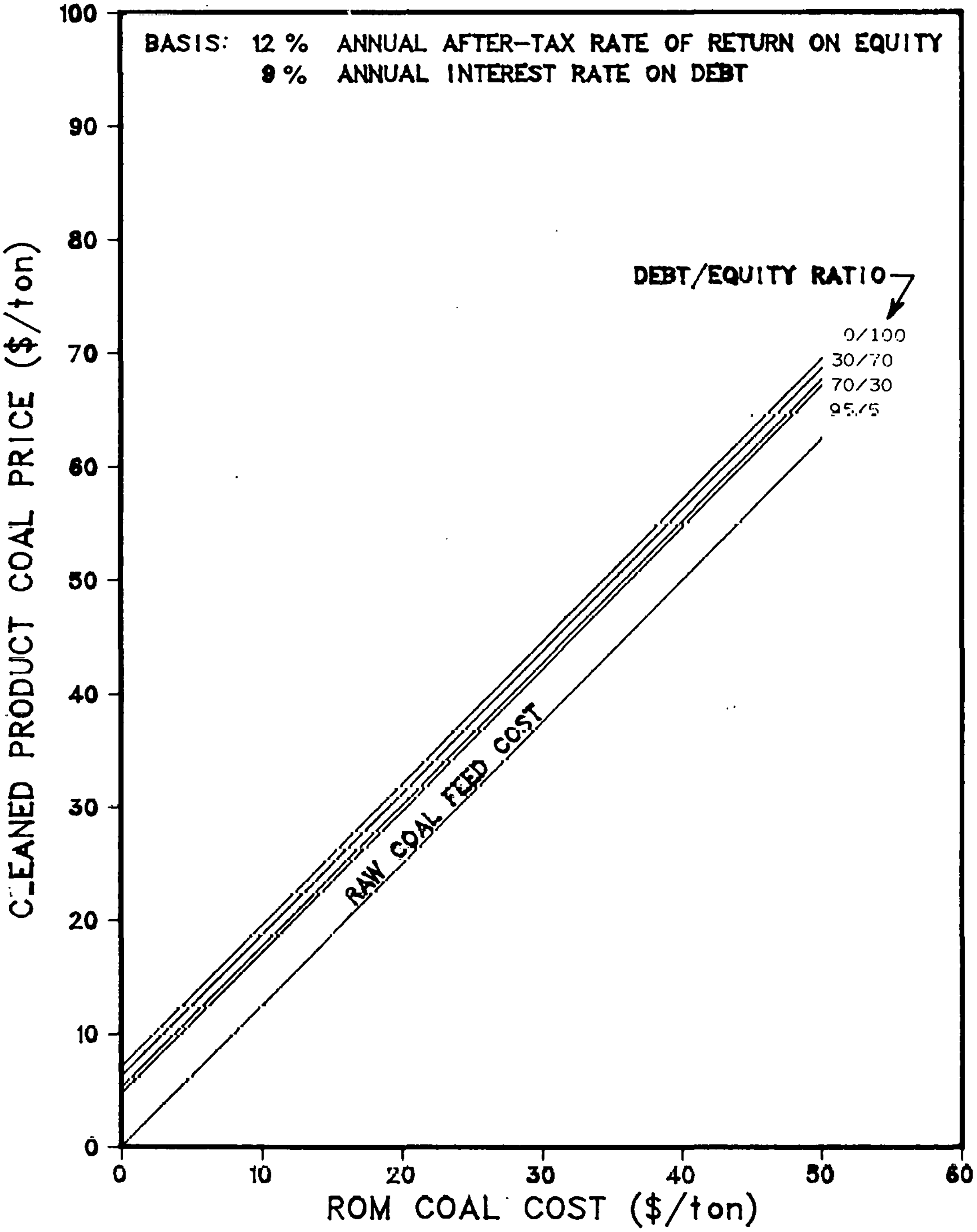


Fig. B-47. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

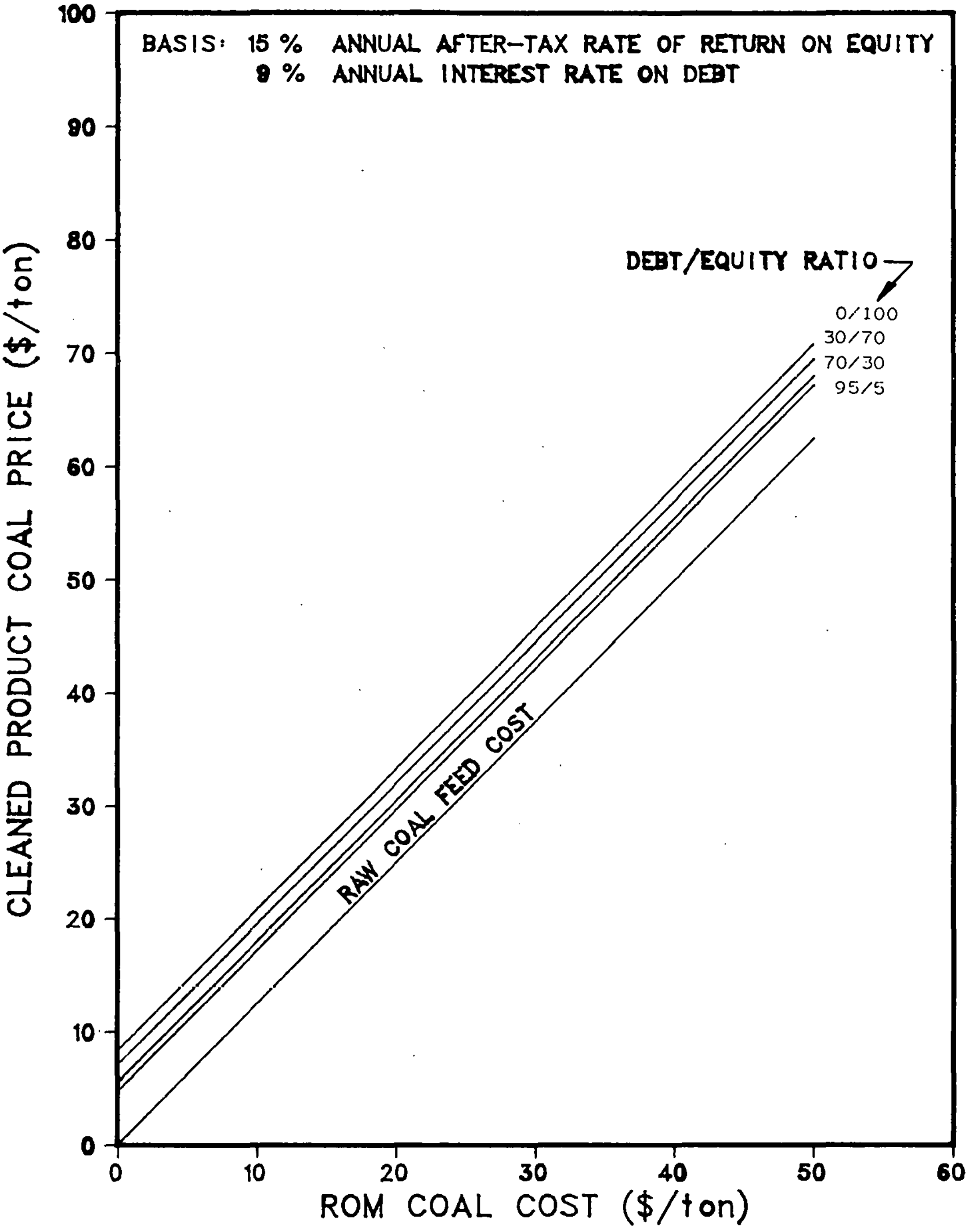


Fig. B-48. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: deep cleaning; 15,000-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

B.3 Plots for Chemical Beneficiation — TRW-Meyers Process

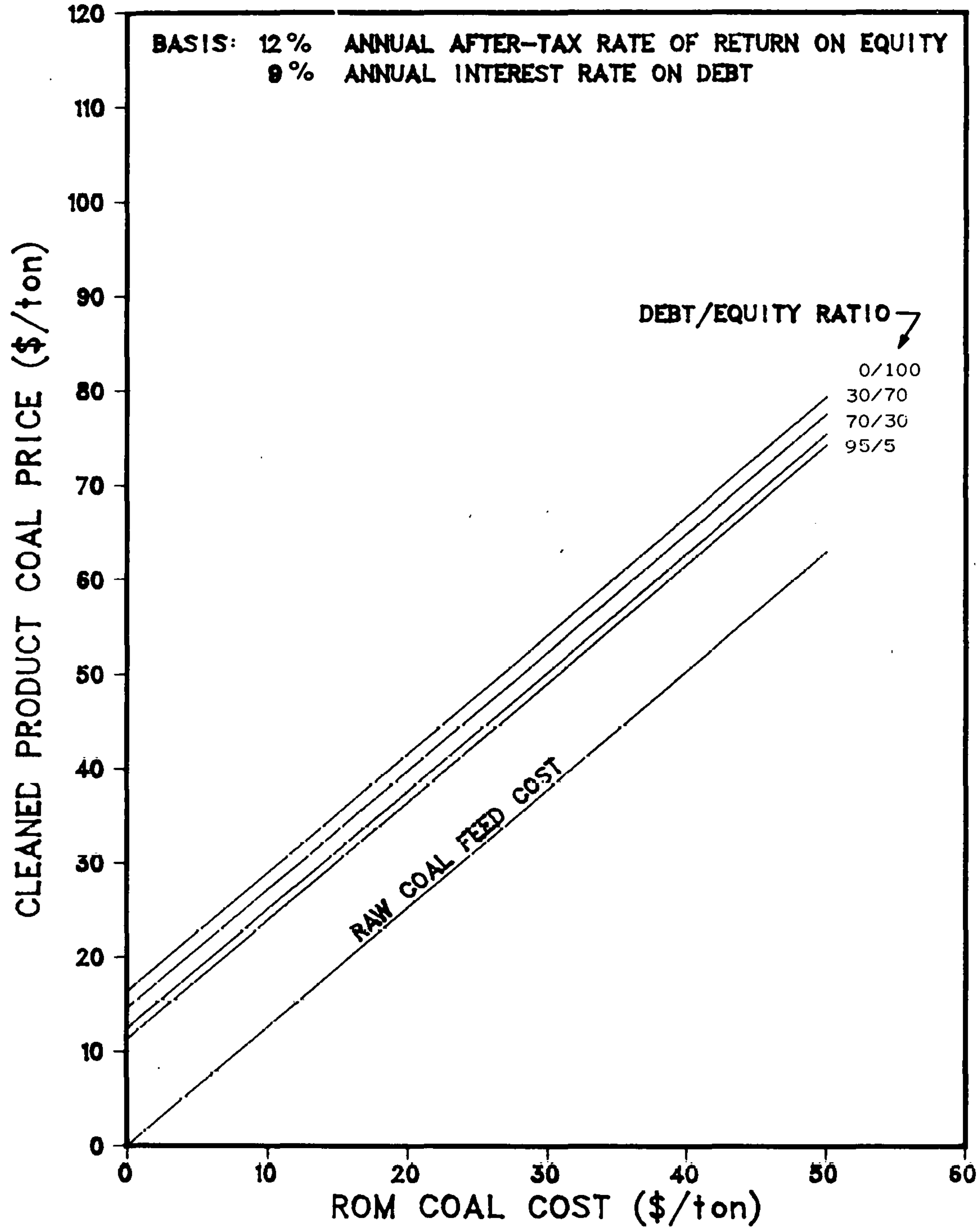


Fig. B-49. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

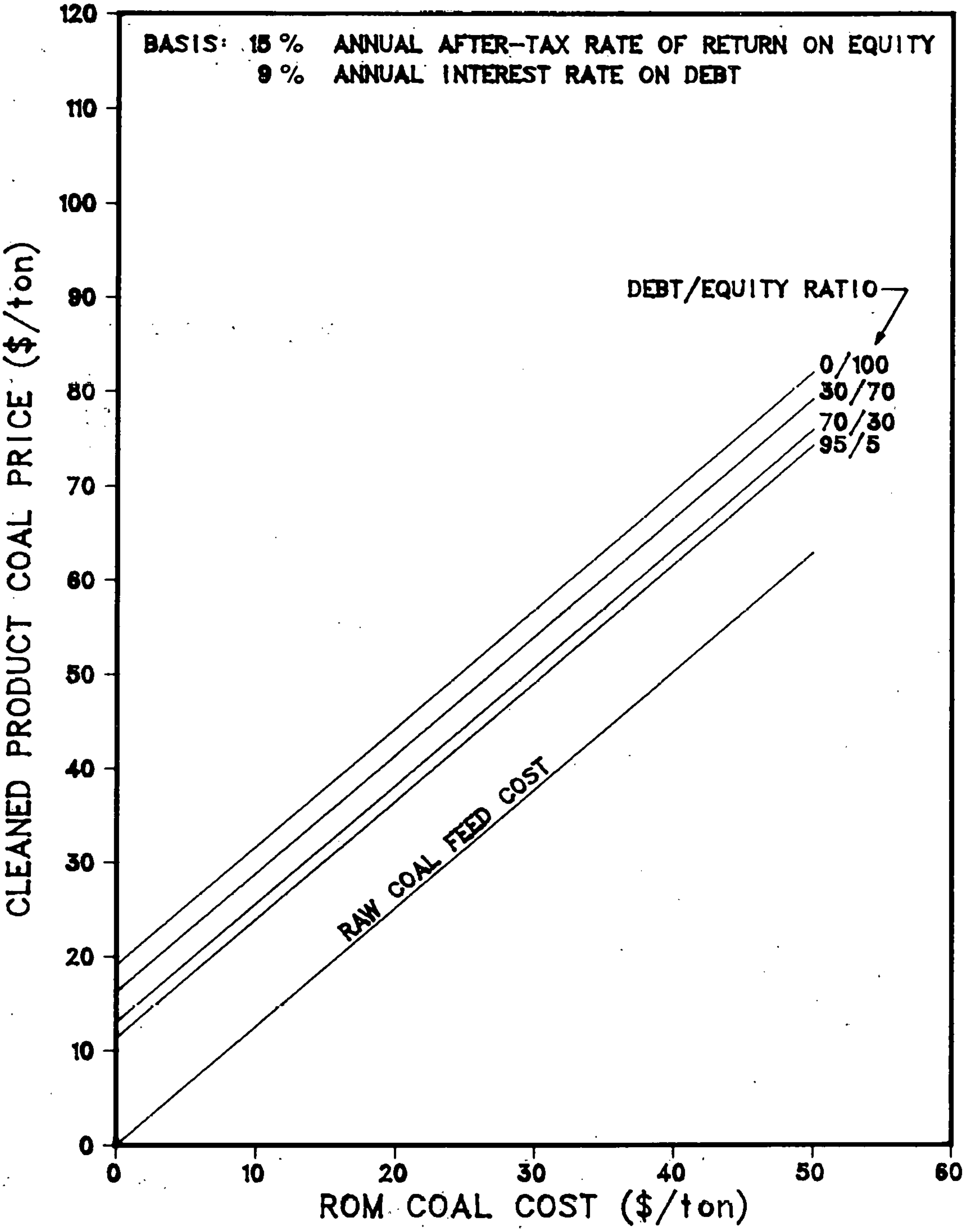


Fig. B-50. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

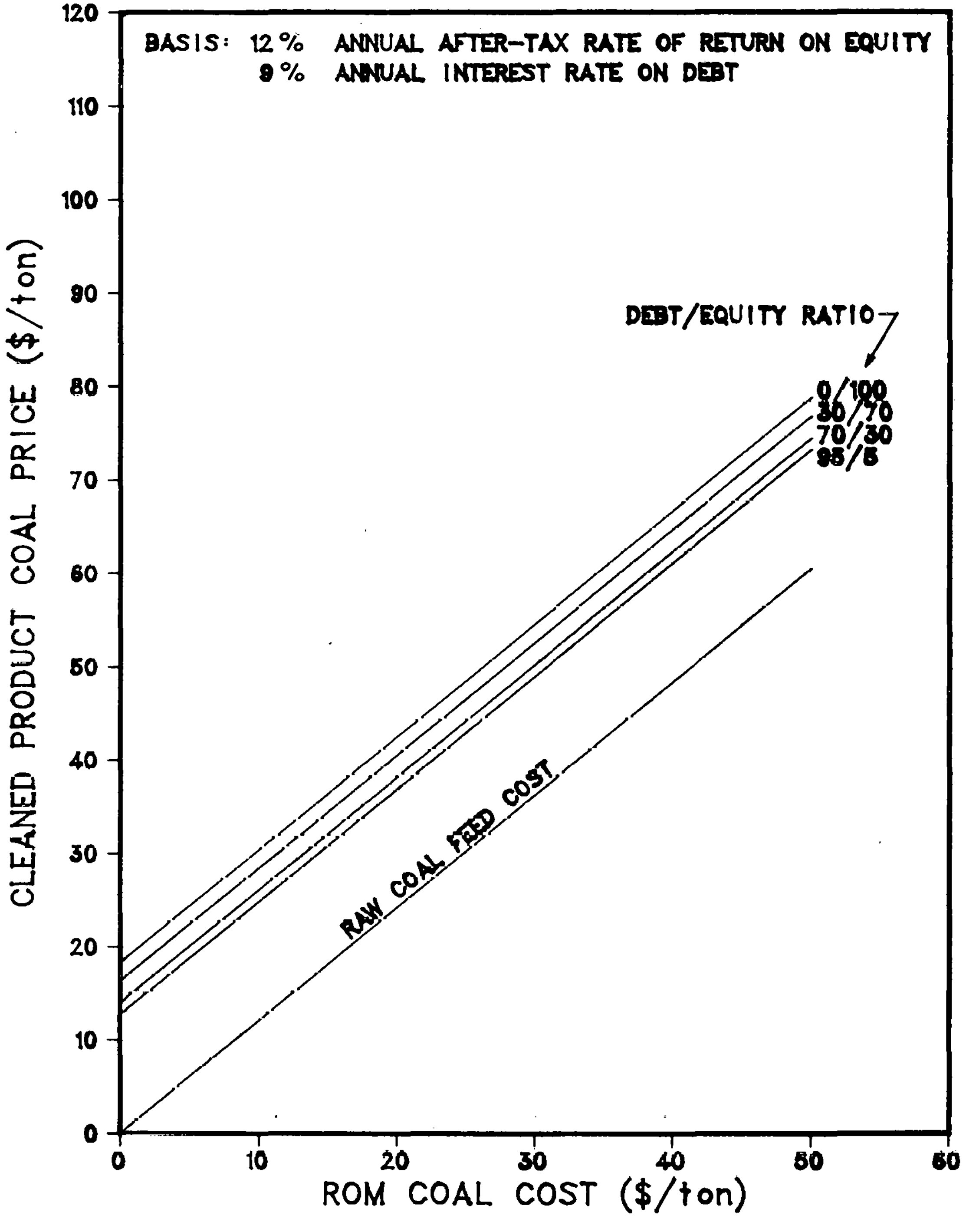


Fig. B-51. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

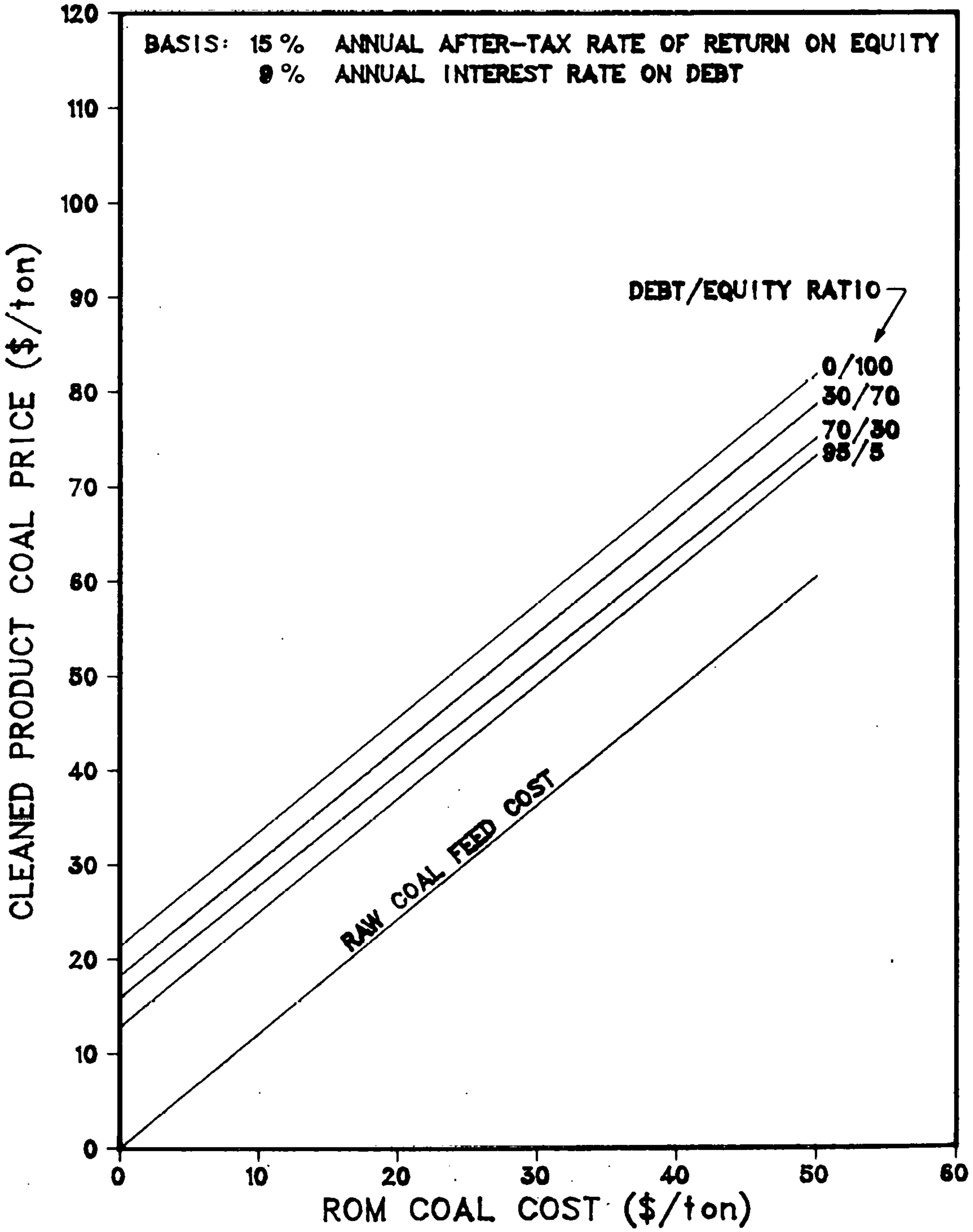


Fig. B-52. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

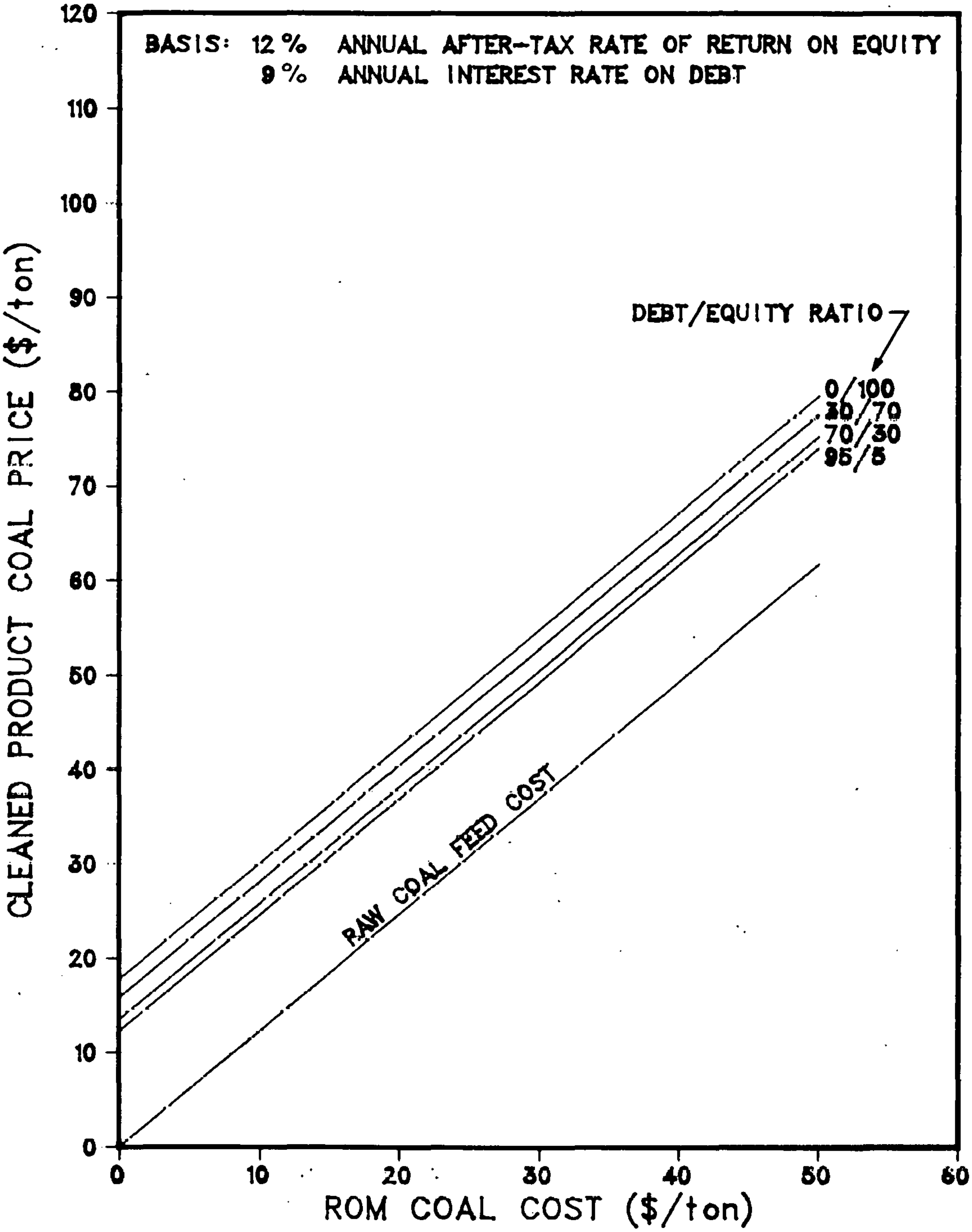


Fig. B-53. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

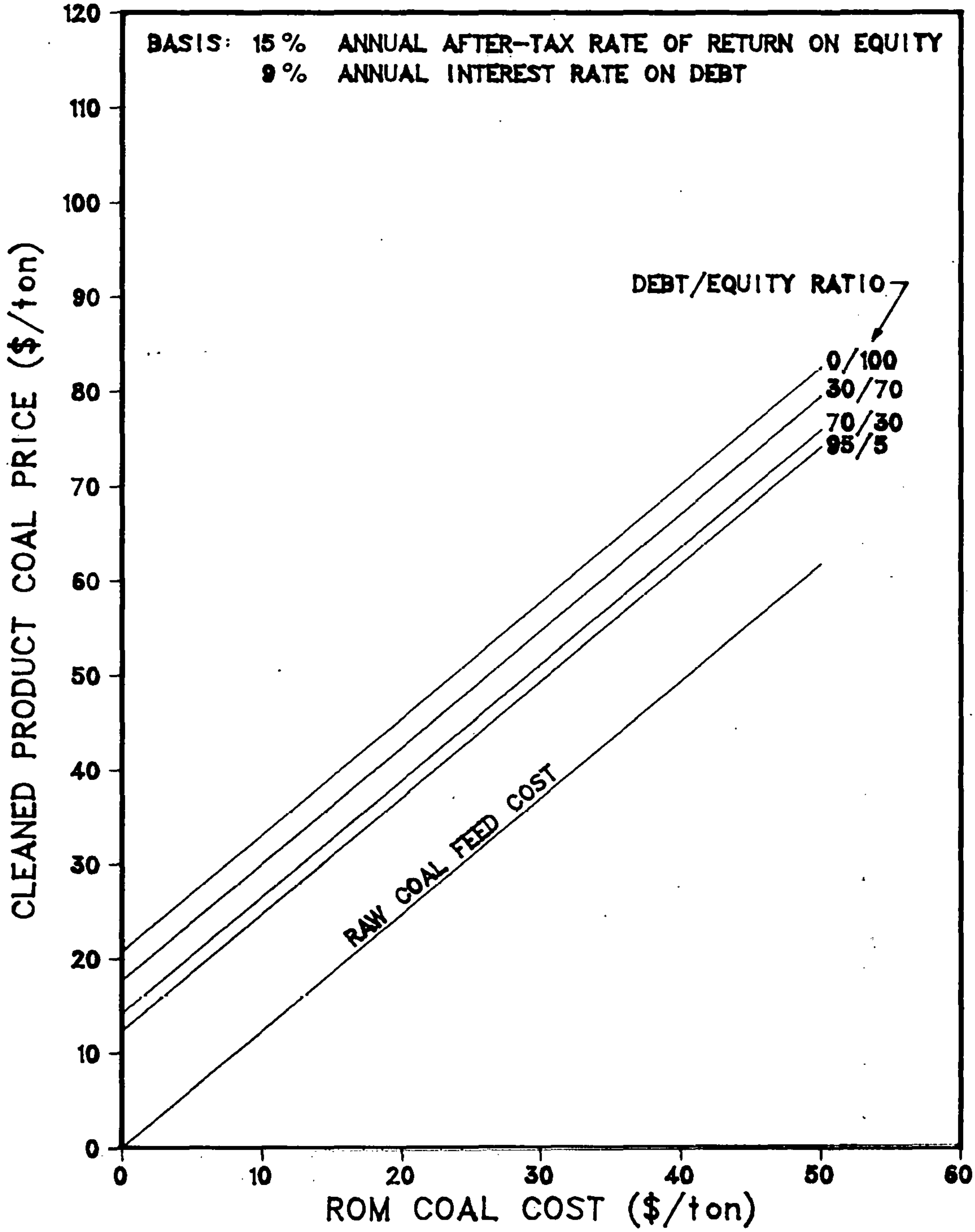


Fig. B-54. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

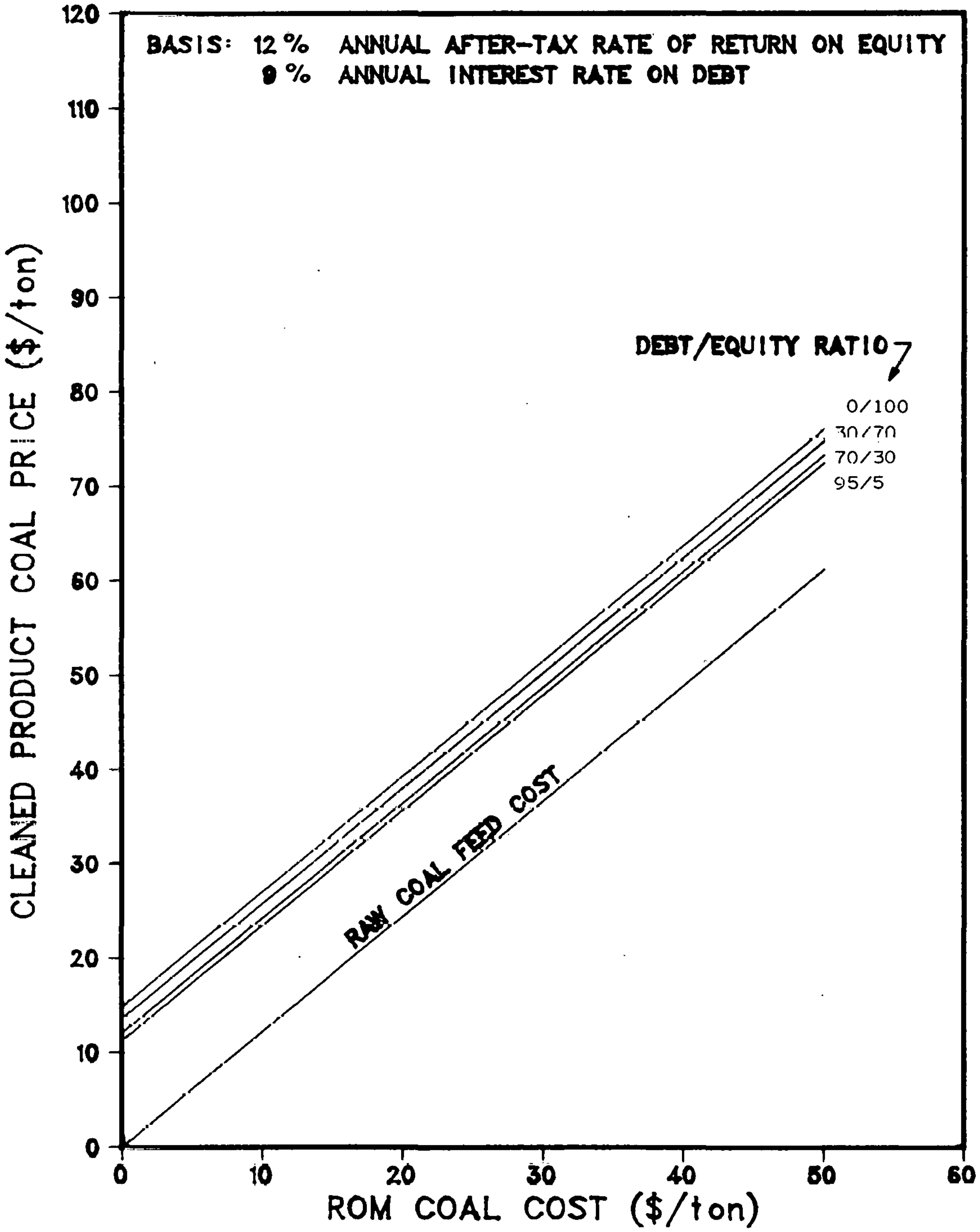


Fig. B-55. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

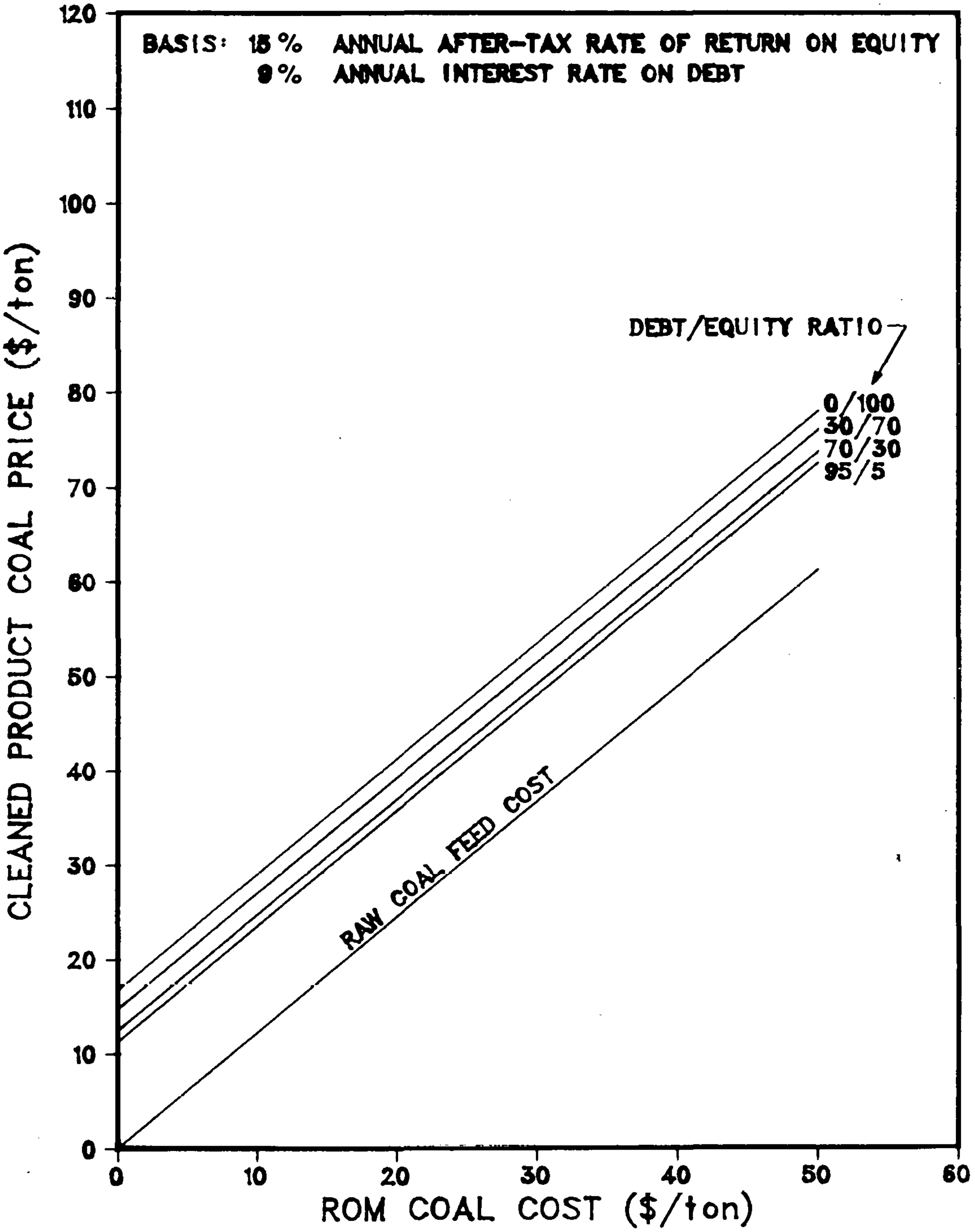


Fig. B-56. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

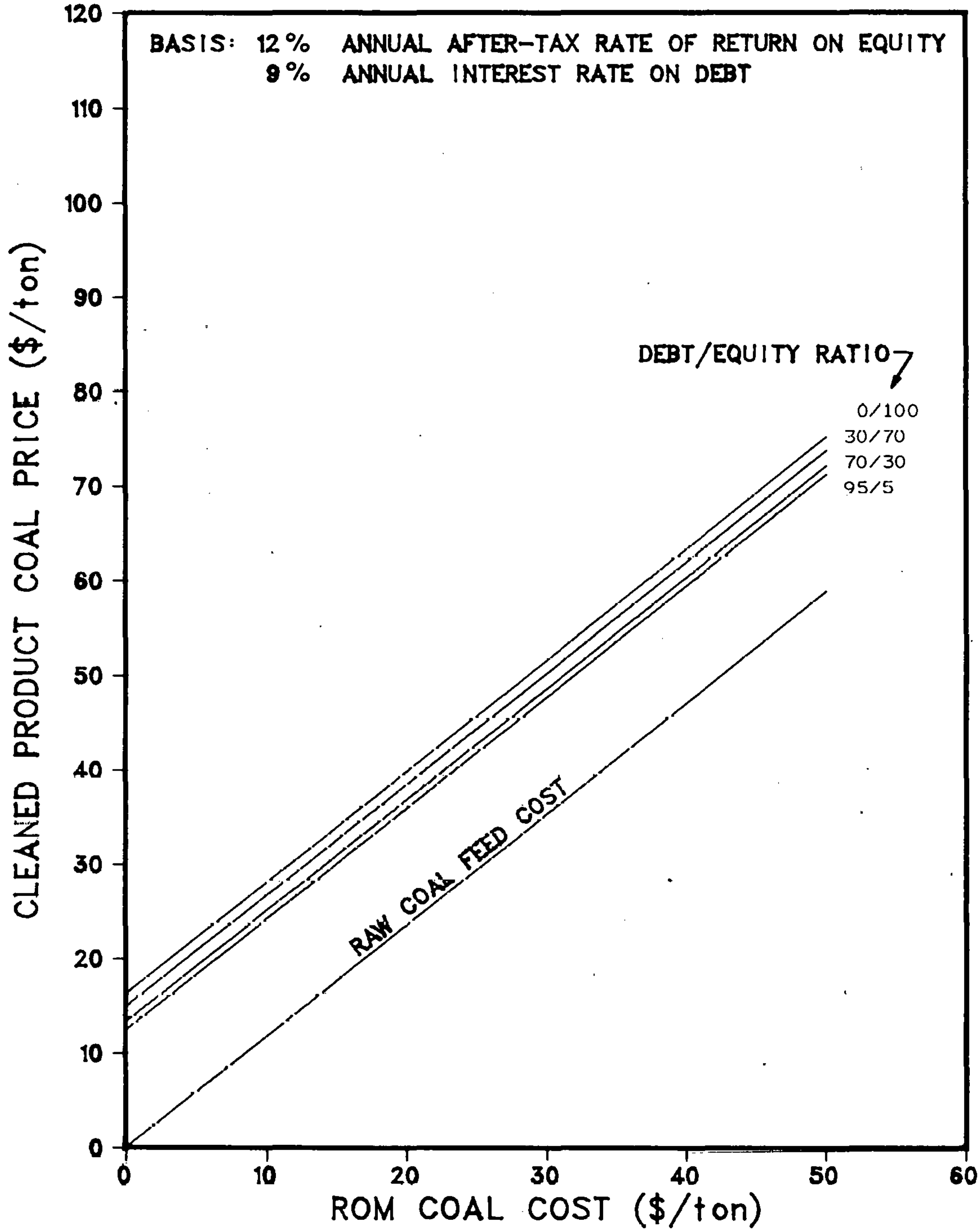


Fig. B-57. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

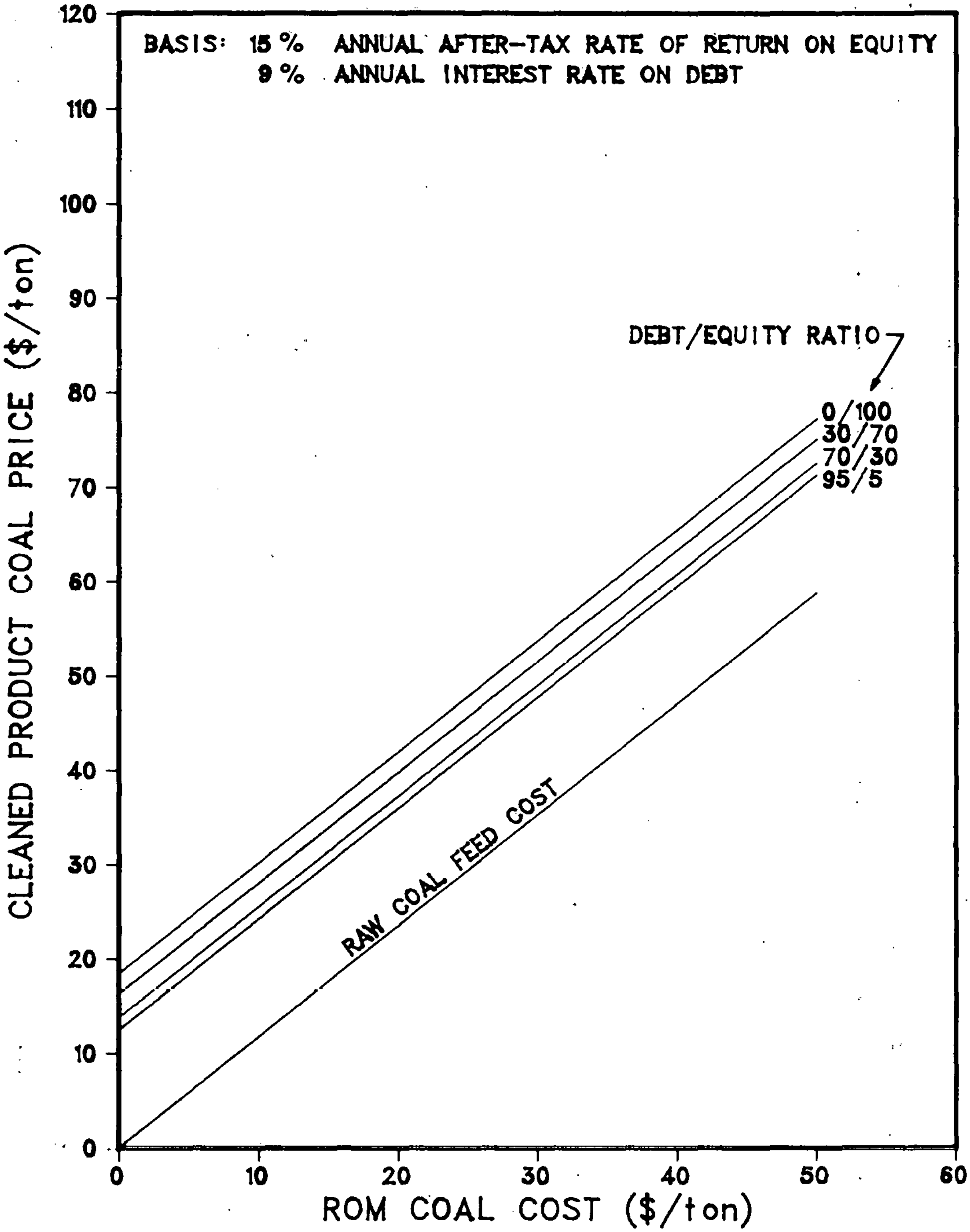


Fig. B-58. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

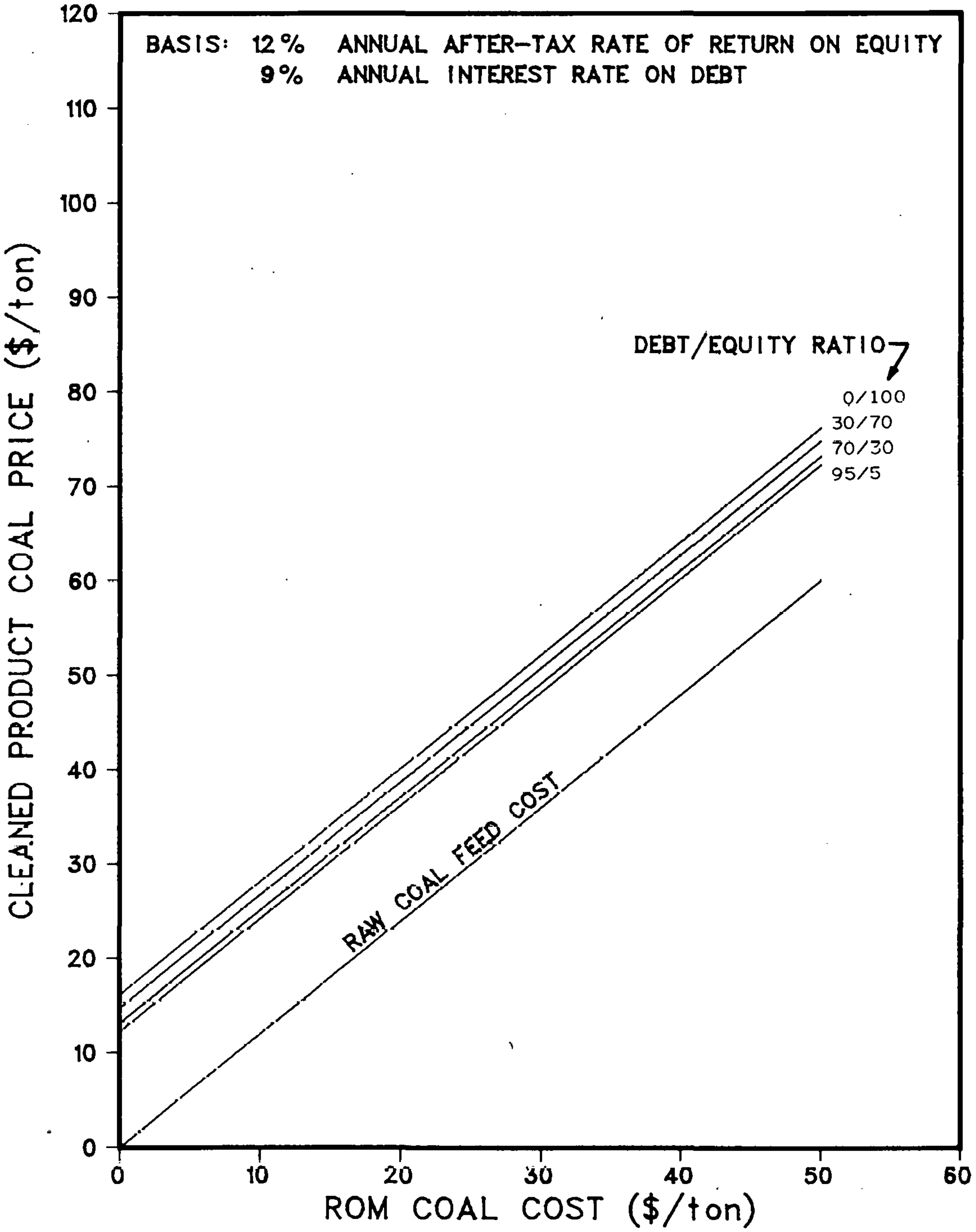


Fig. B-59. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

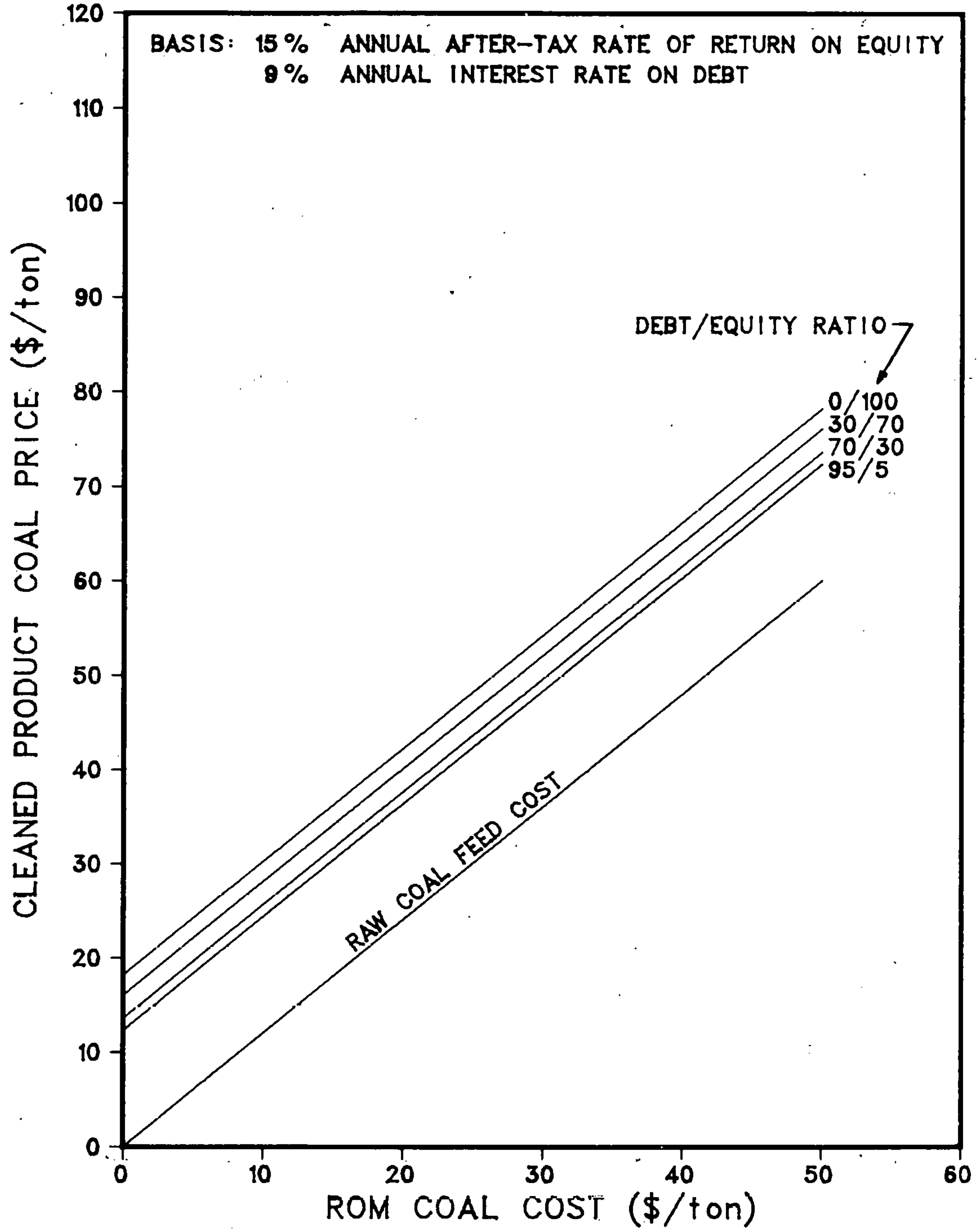


Fig. B-60. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 1500-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

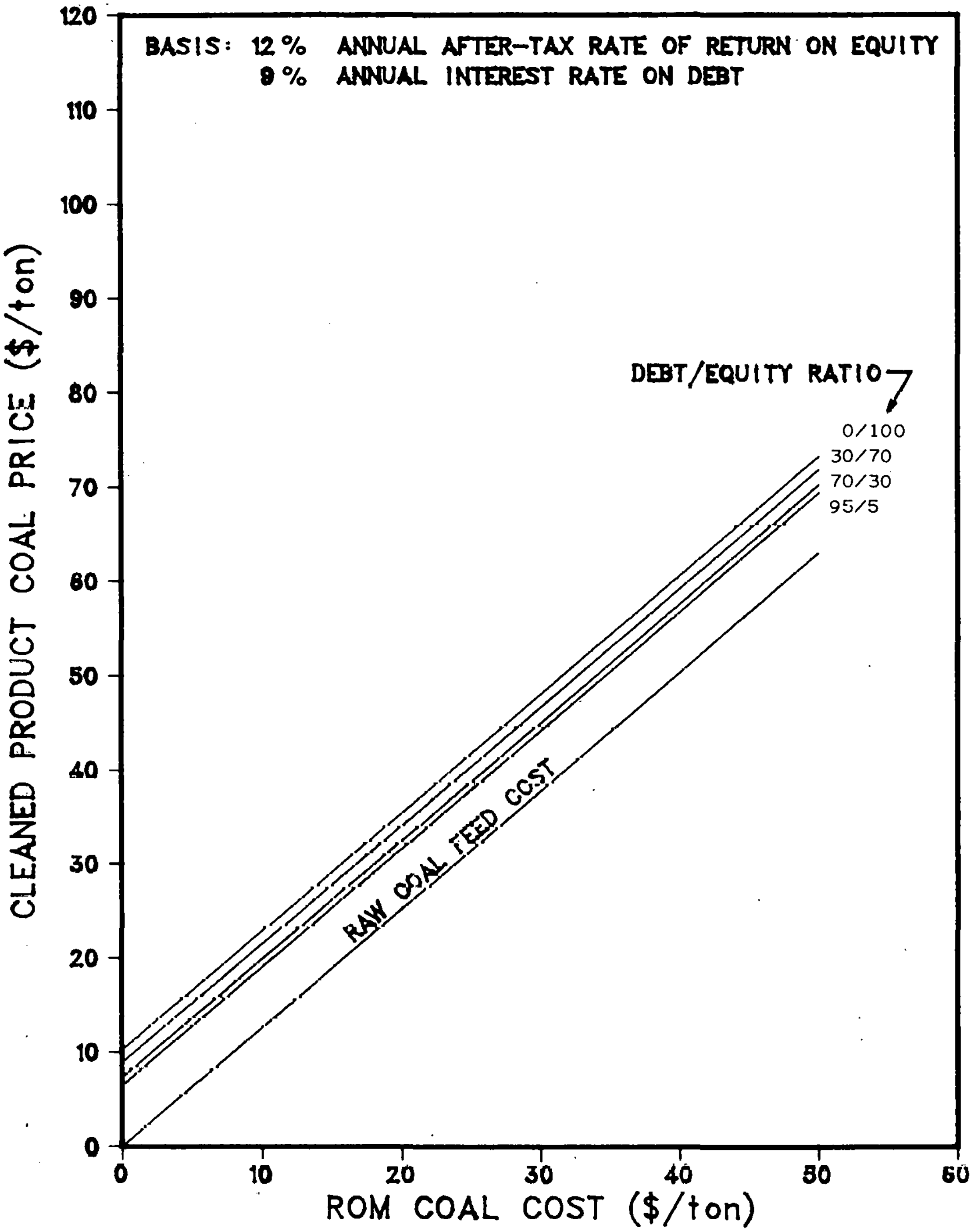


Fig. B-61. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

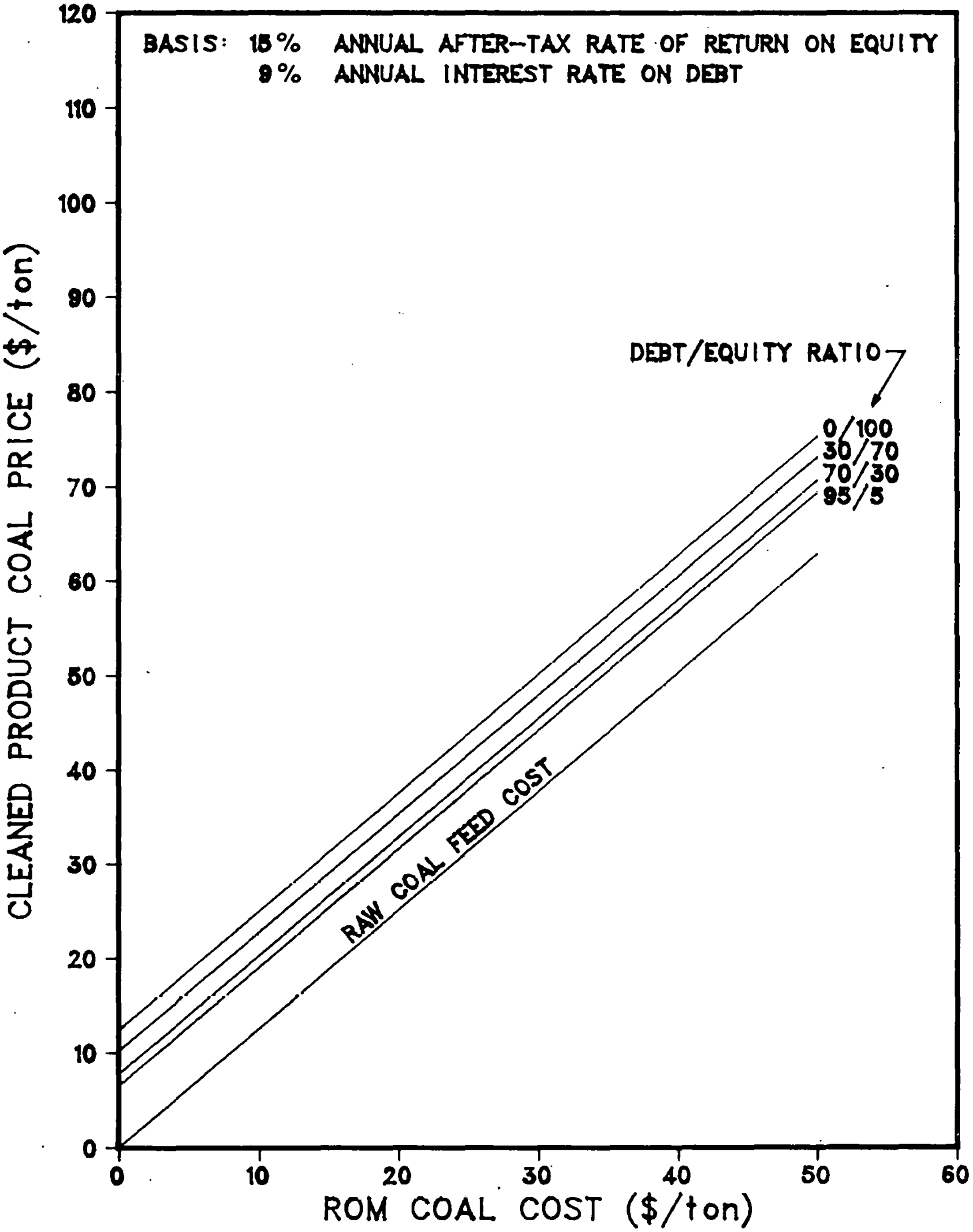


Fig. B-62. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

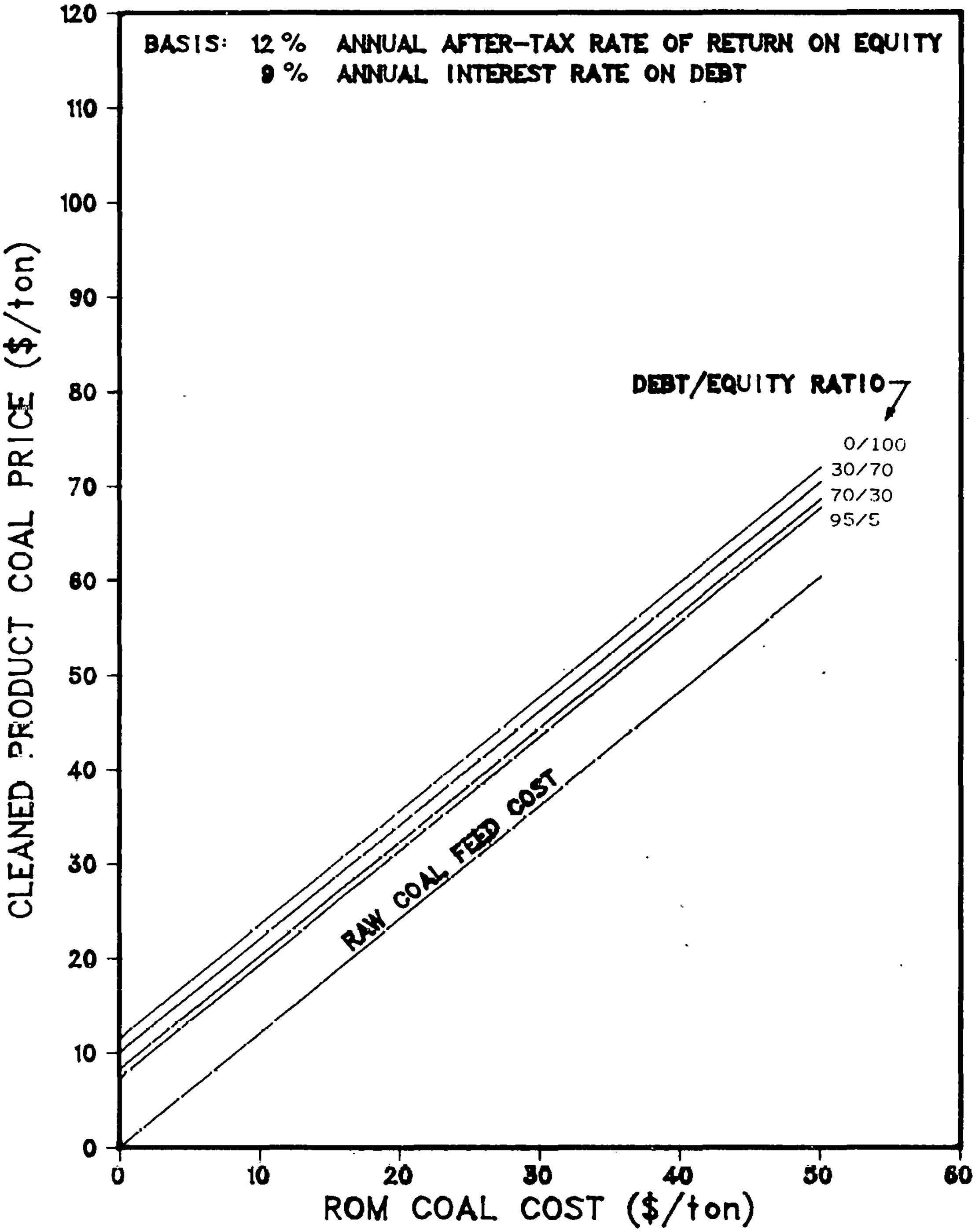


Fig. B-63. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

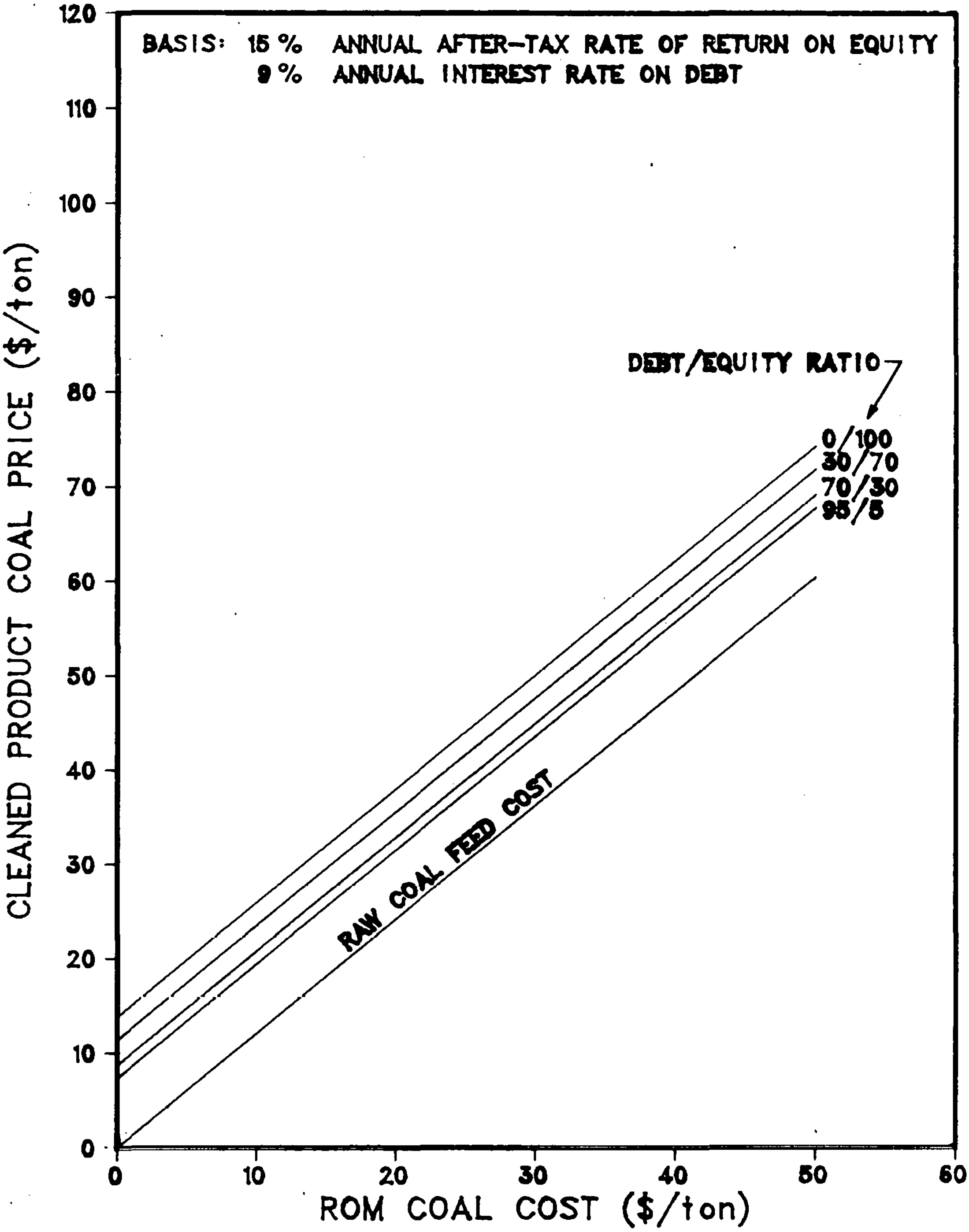


Fig. B-64. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

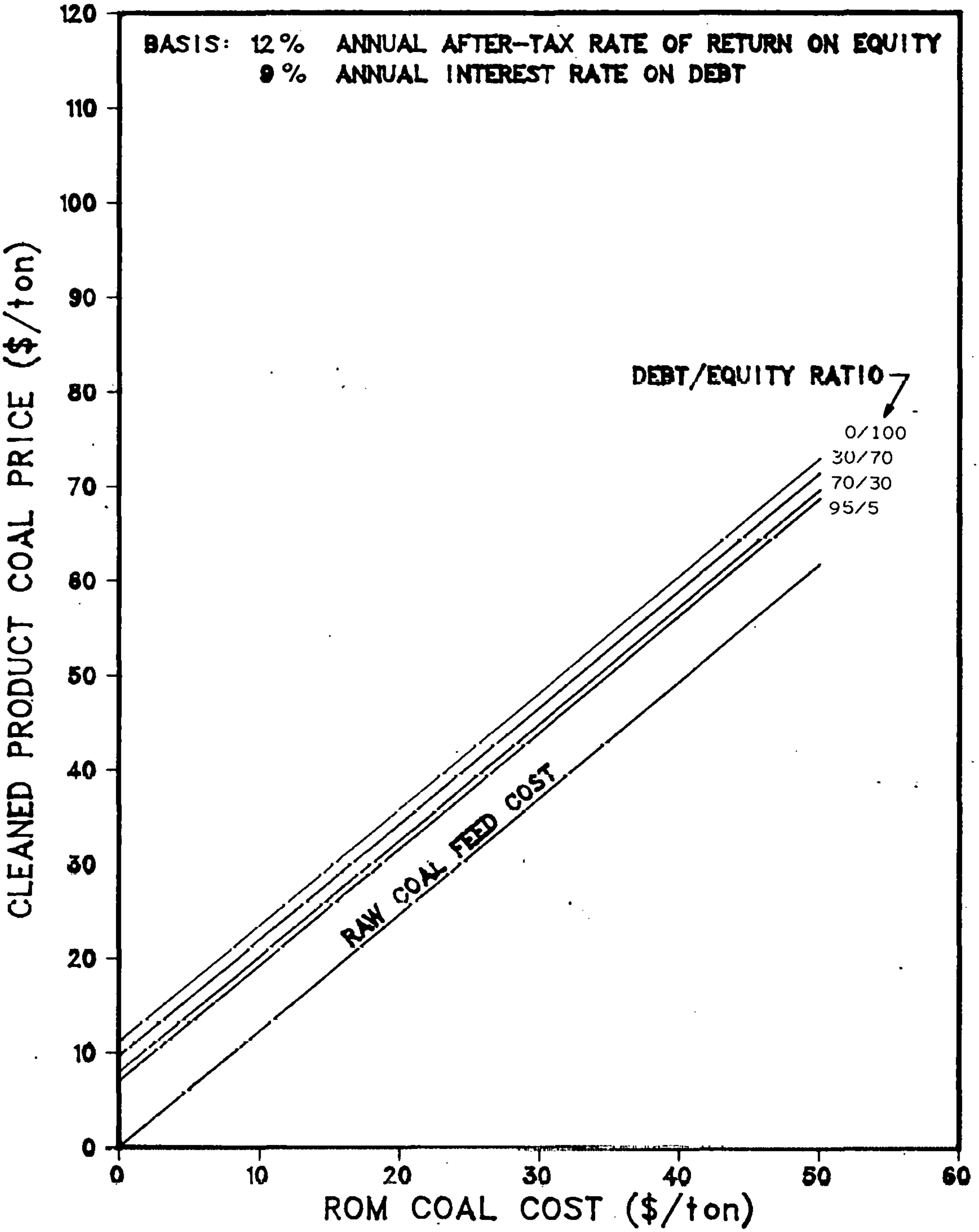


Fig. B-65. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

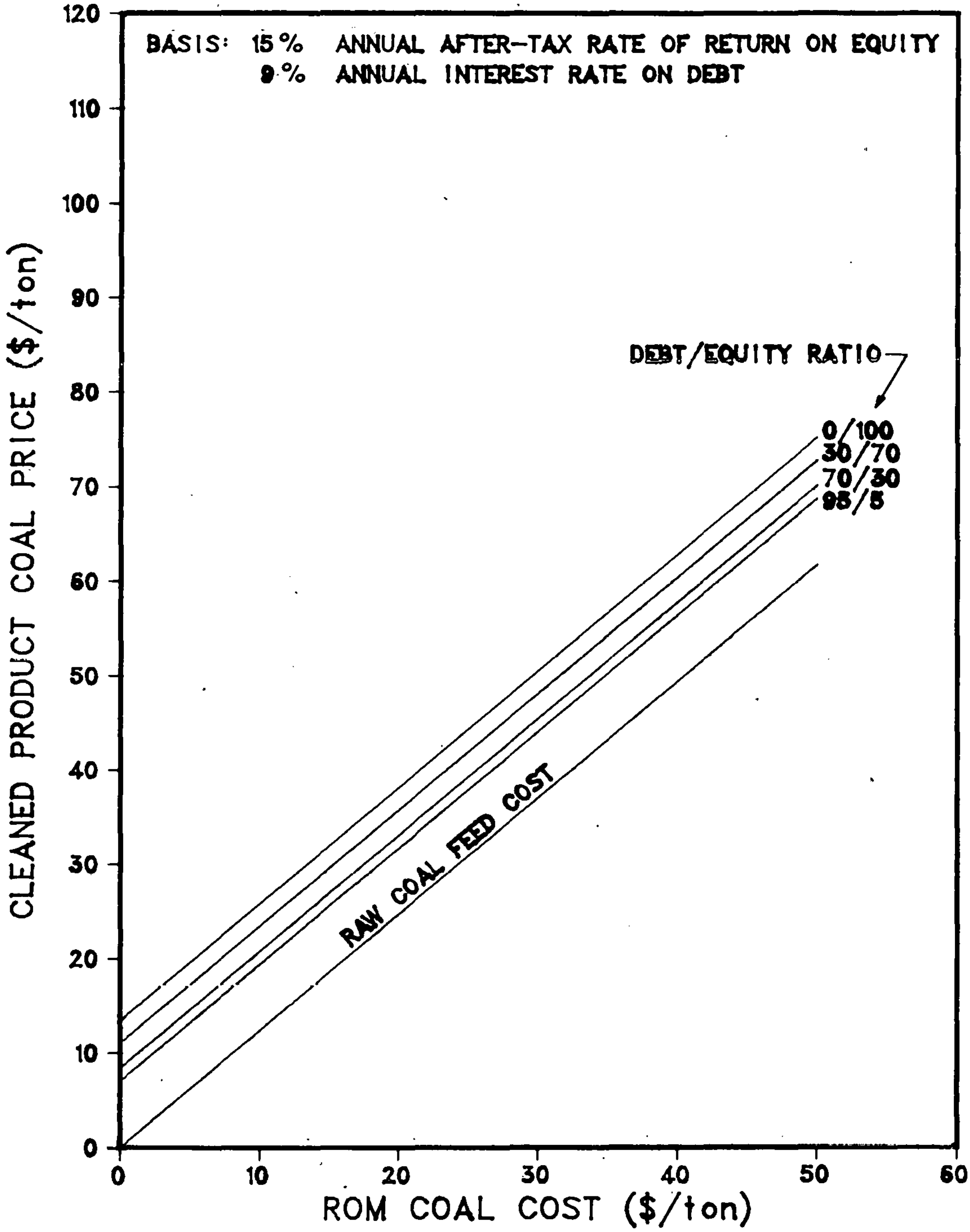


Fig. B-66. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

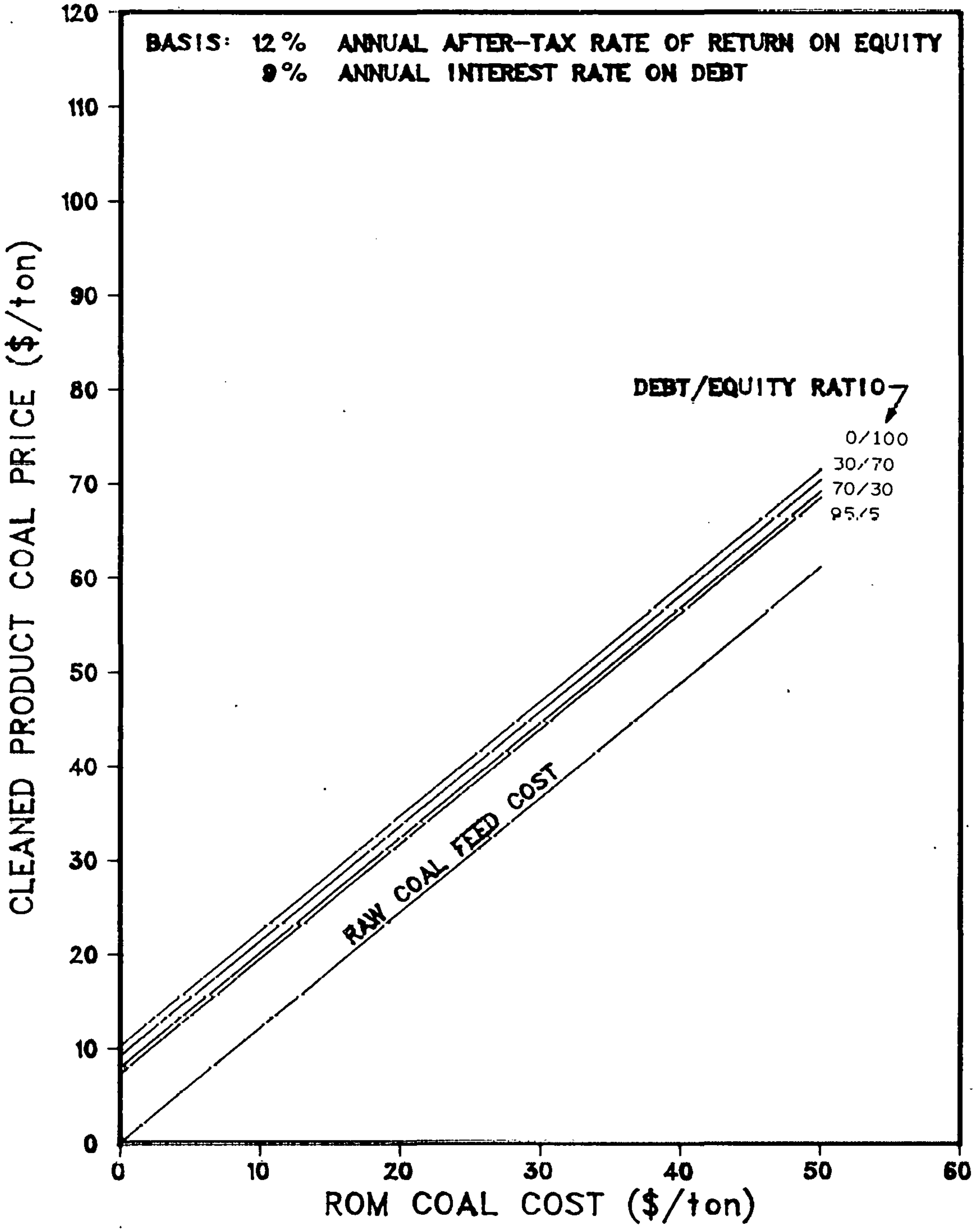


Fig. B-67. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

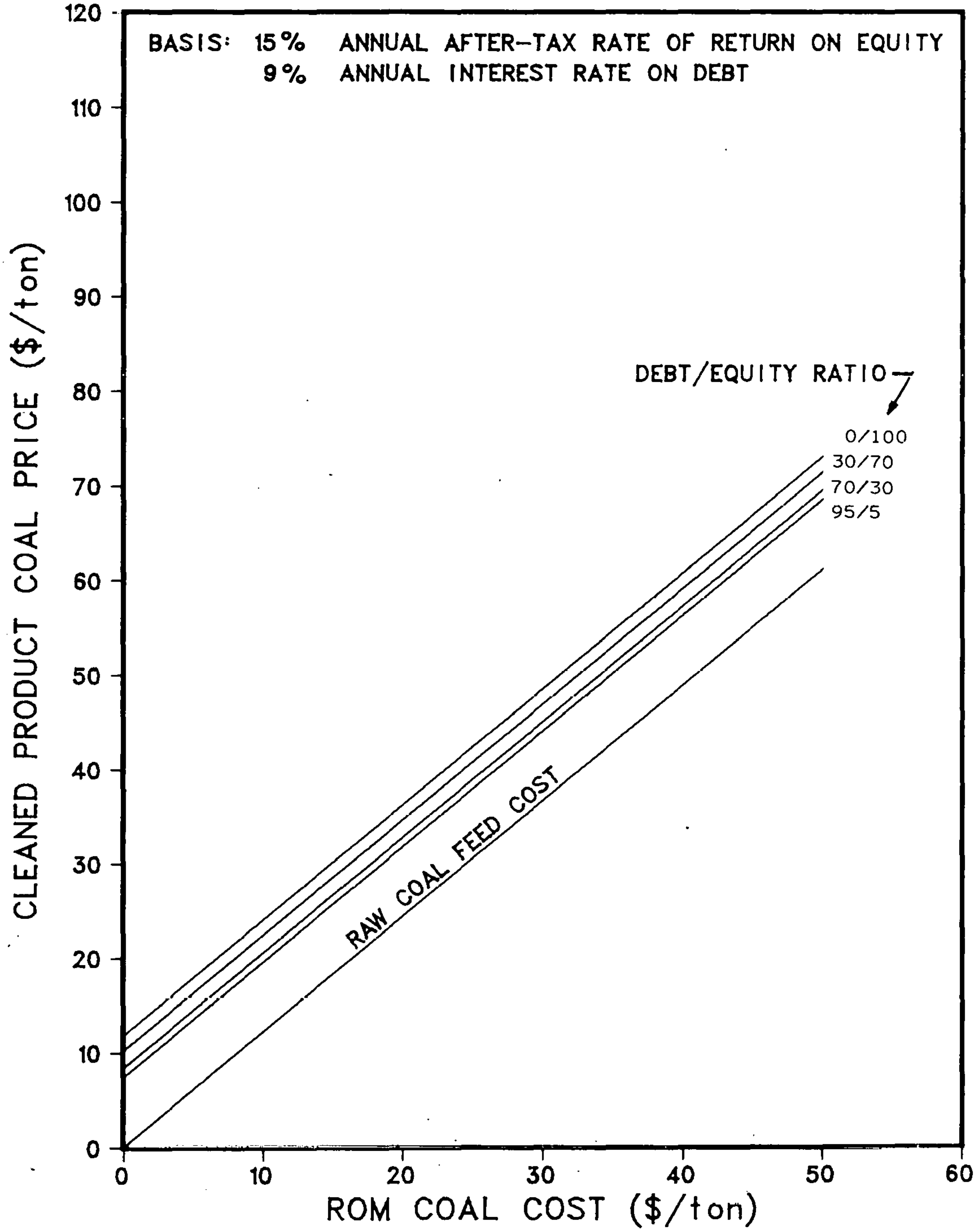


Fig. B-68. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

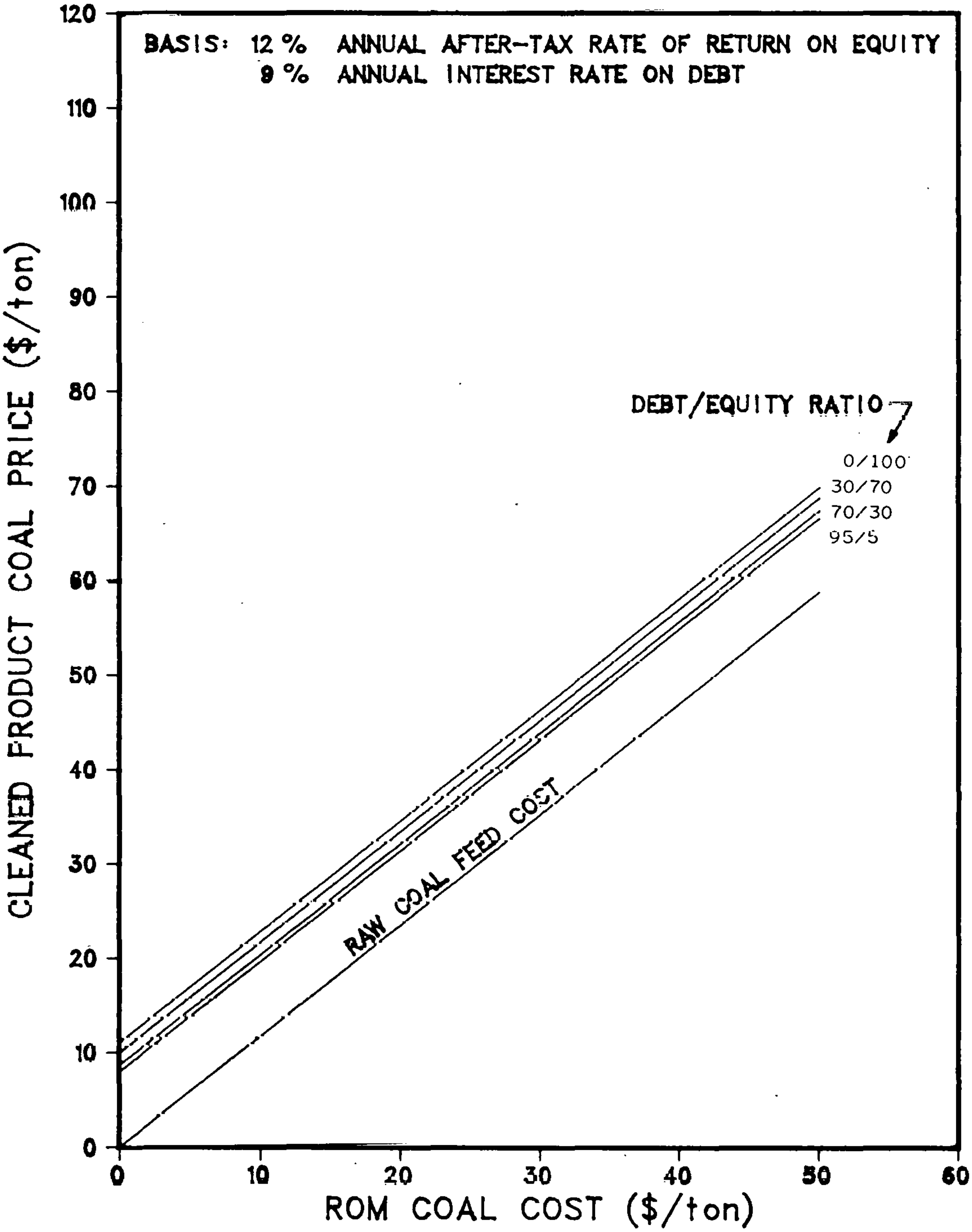


Fig. B-69. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

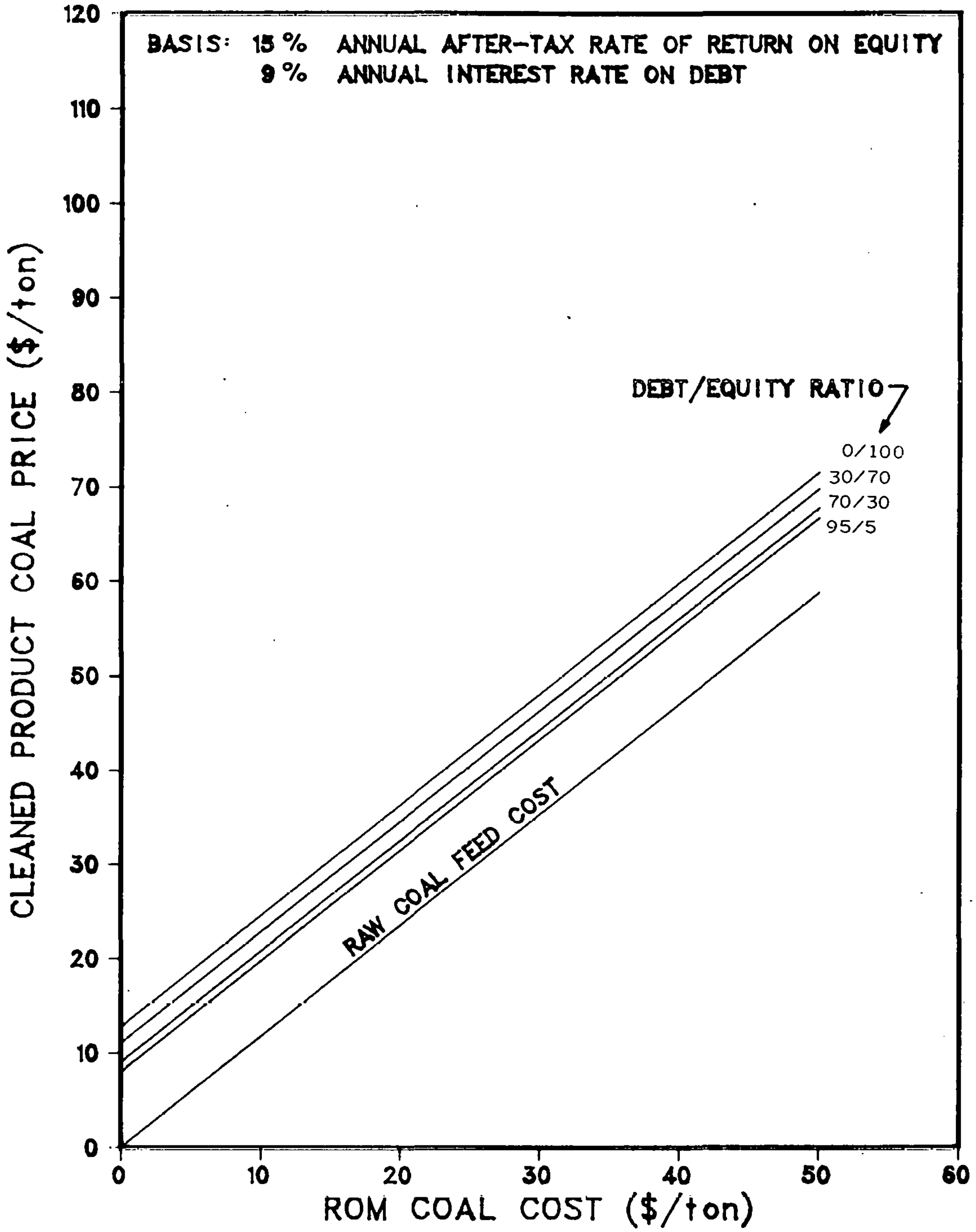


Fig. B-70. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

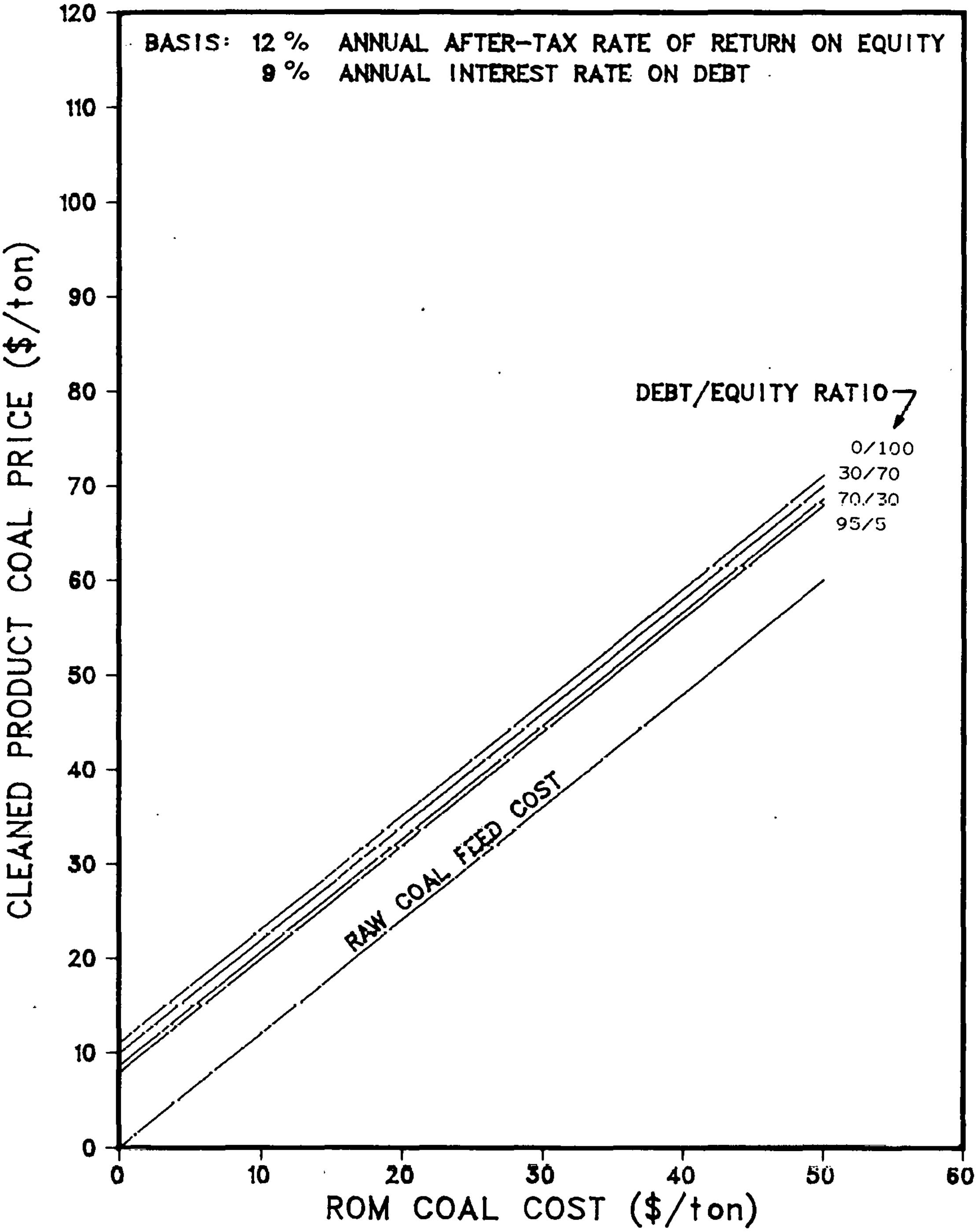


Fig. B-71. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

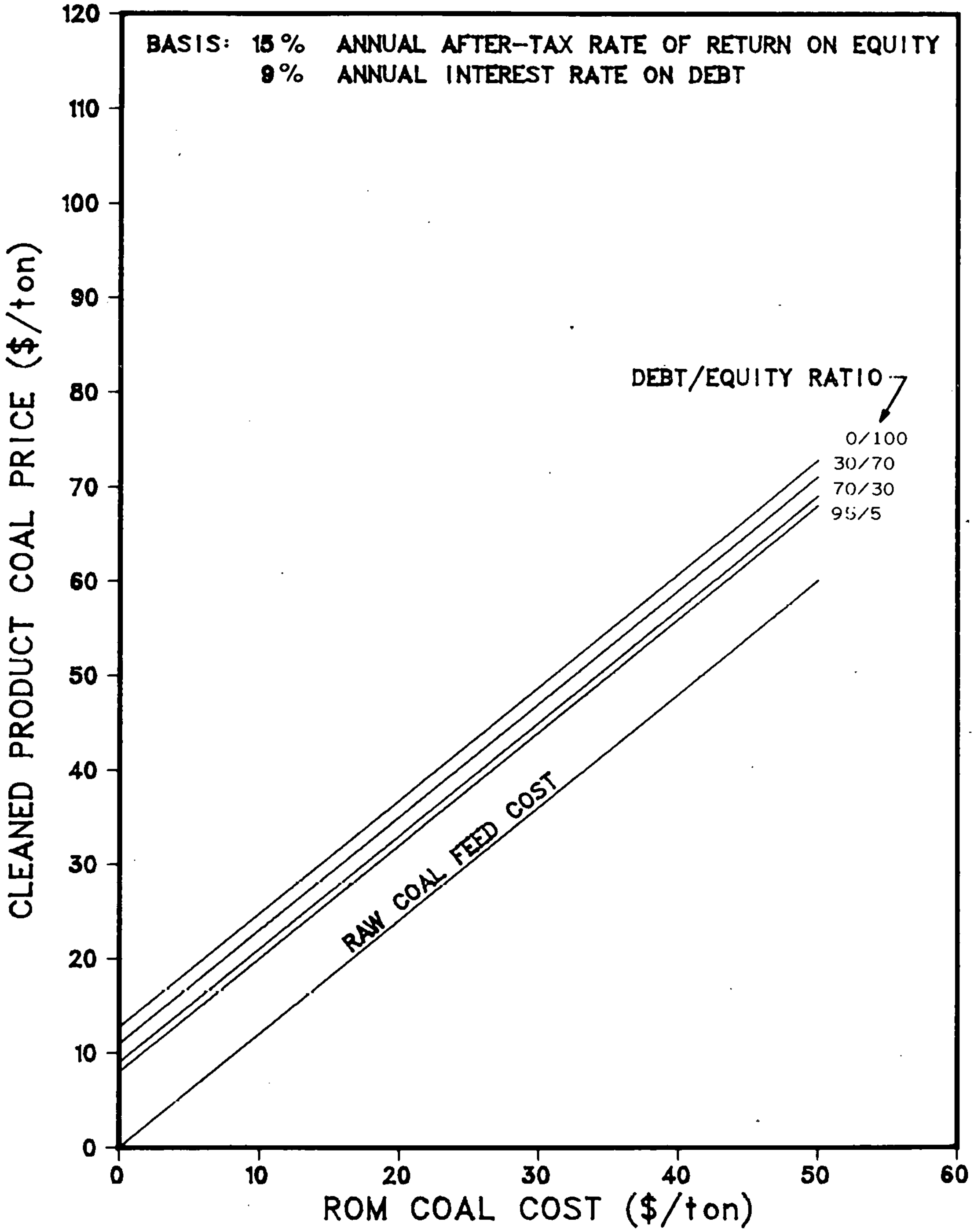


Fig. B-72. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: TRW-Meyers process; 15,000-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

B.4 Plots for Chemical Beneficiation — Battelle Hydrothermal Coal Process (BHCP)

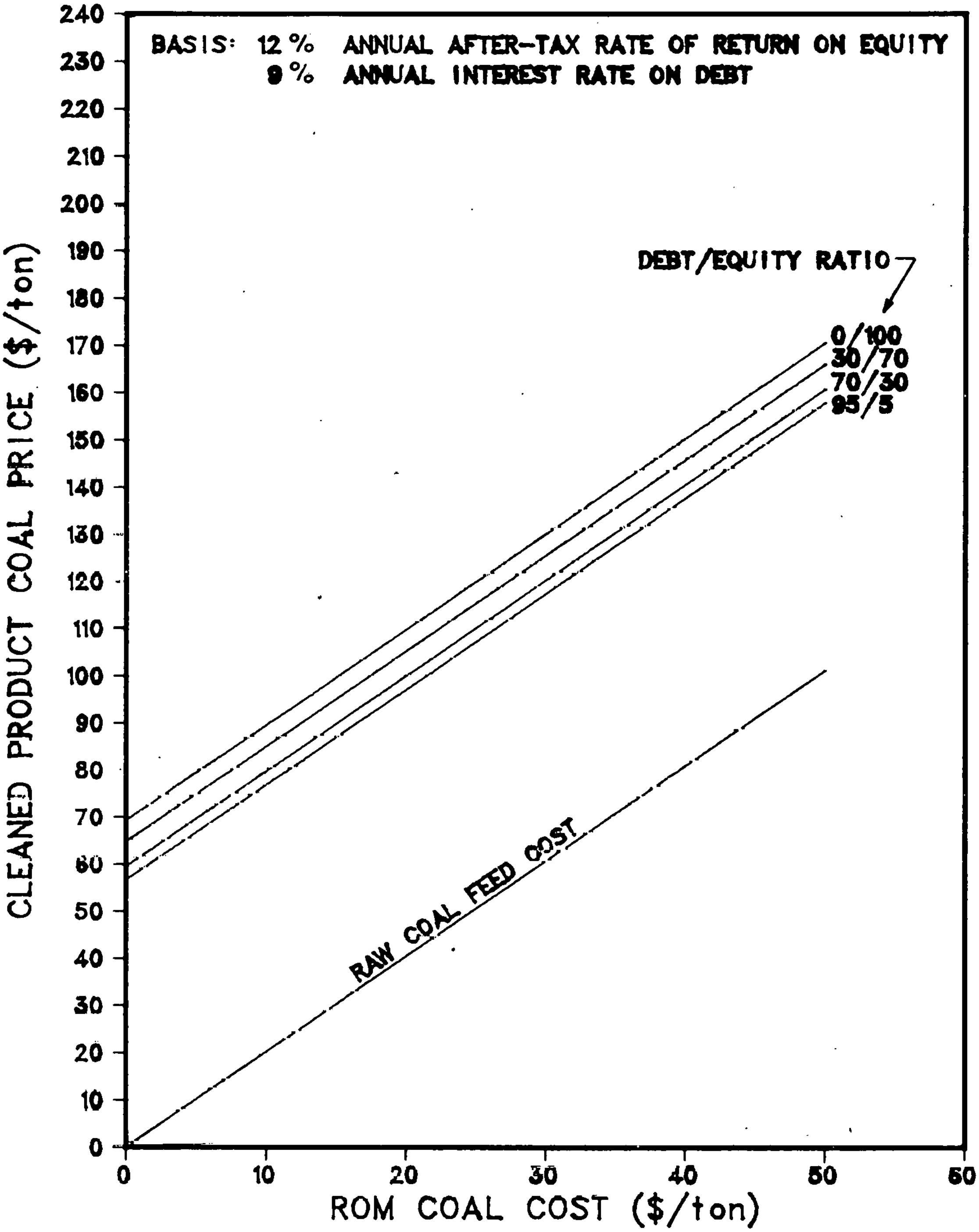


Fig. B-73. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

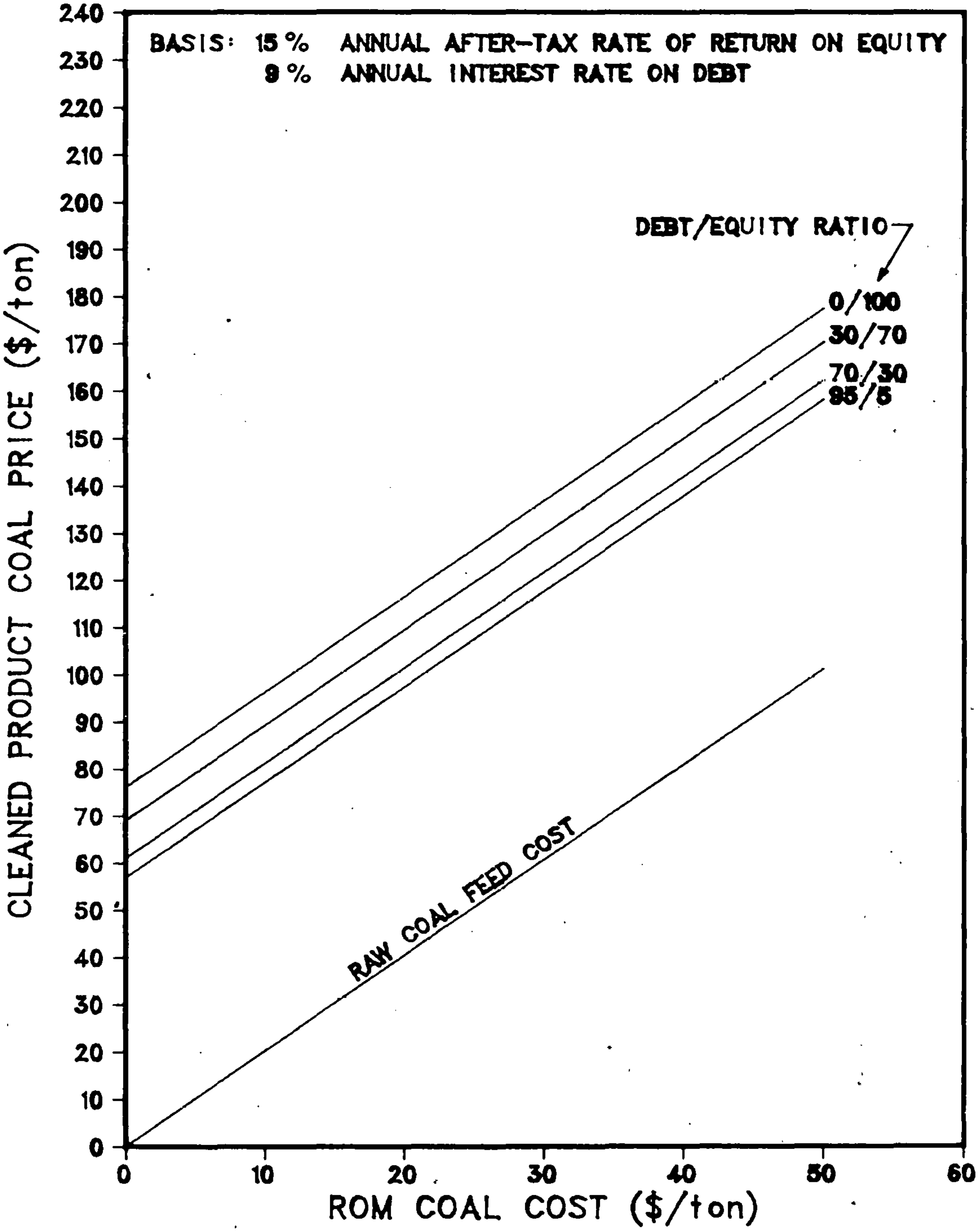


Fig. B-74. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters; BHCP; 1500-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

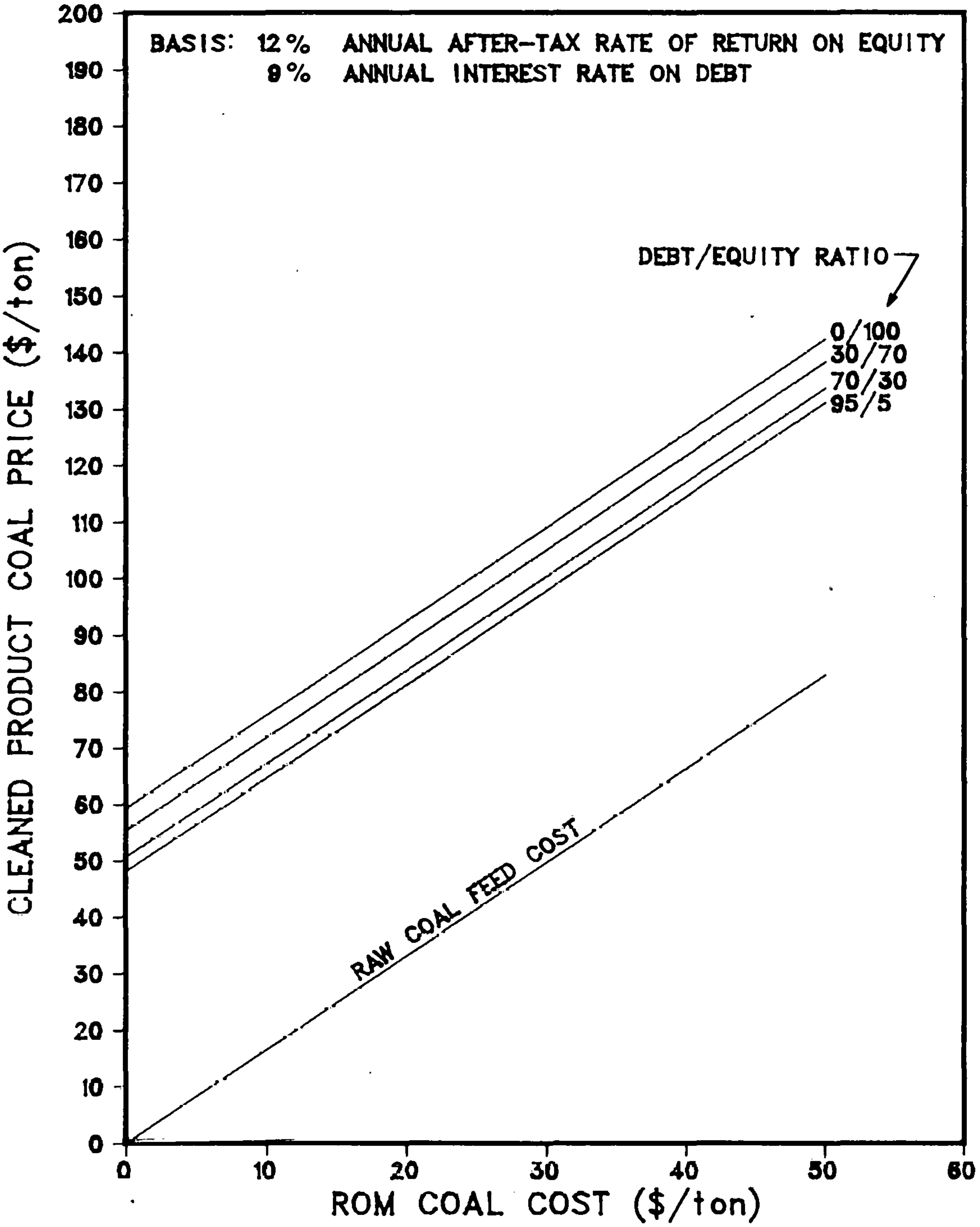


Fig. B-75. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

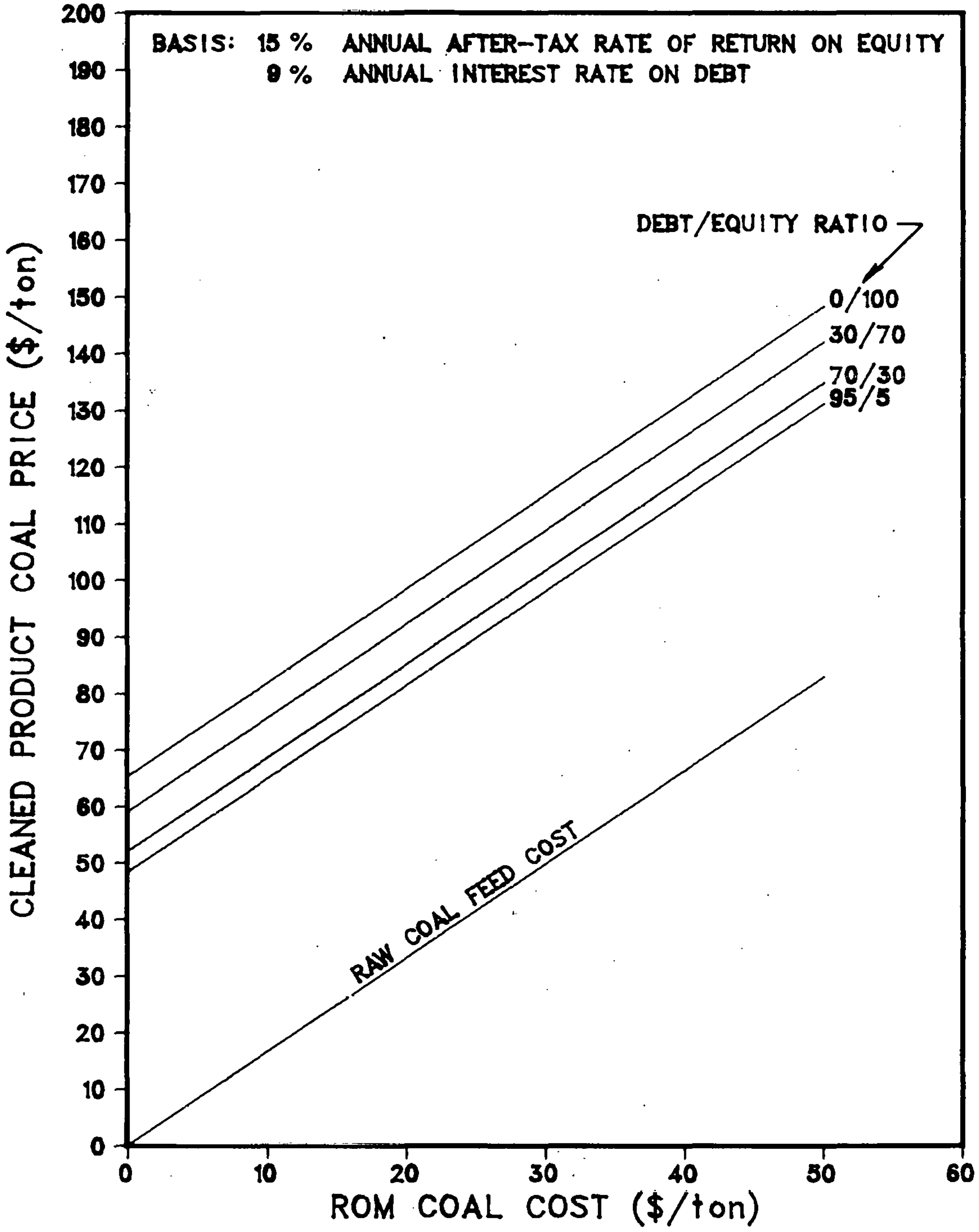


Fig. B-76. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters; BHCP; 1500-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

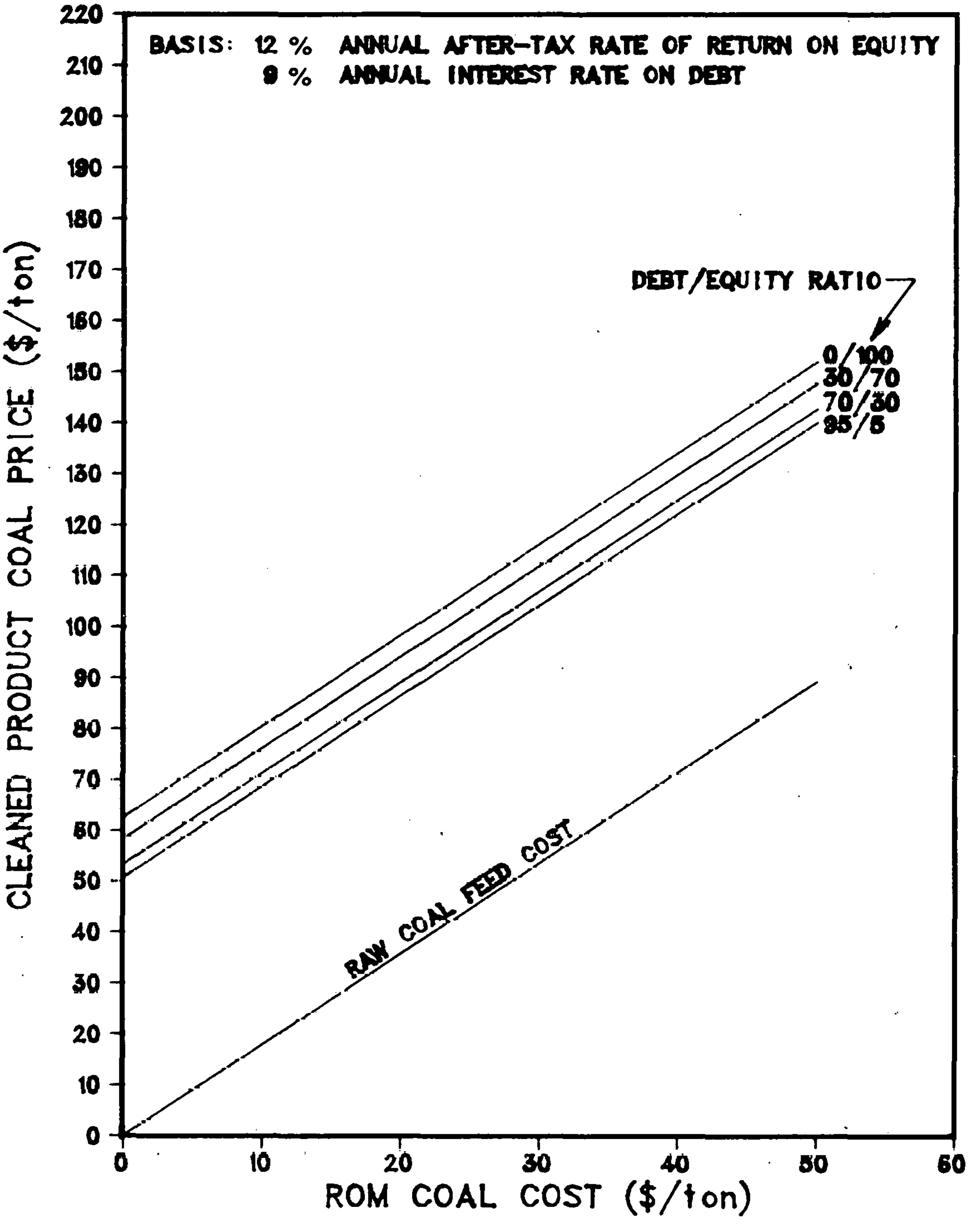


Fig. B-77. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

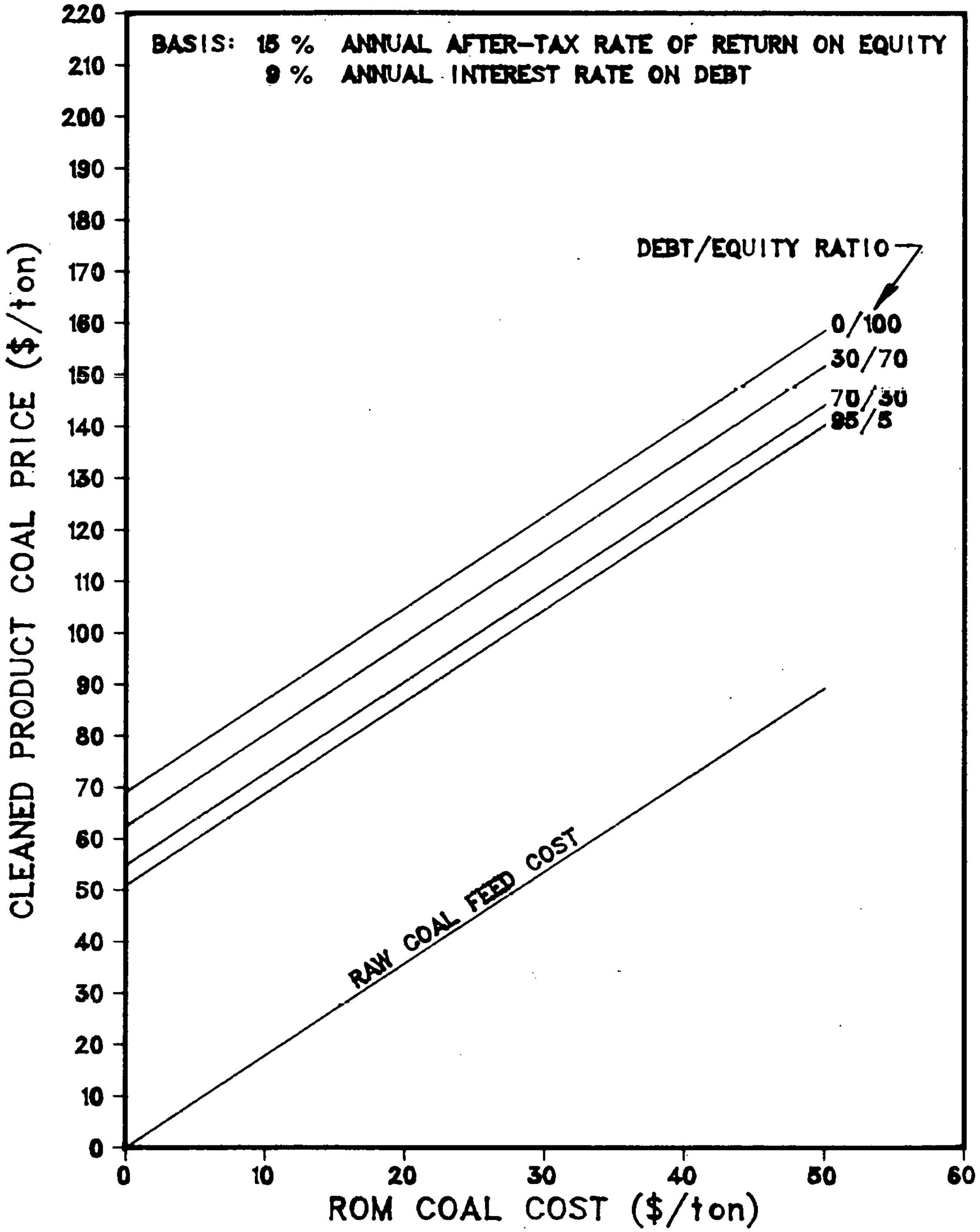


Fig. B-78. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

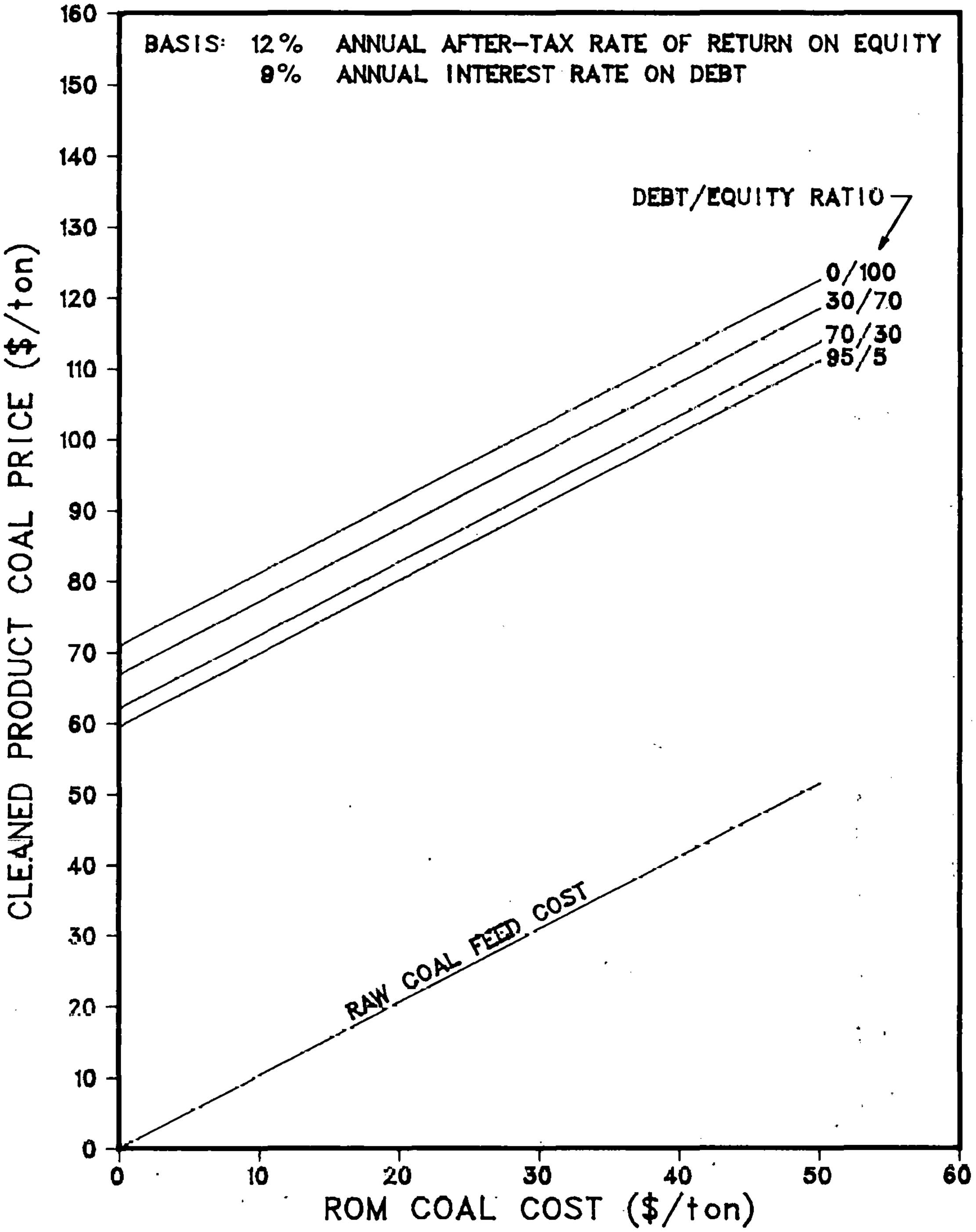


Fig. B-79. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

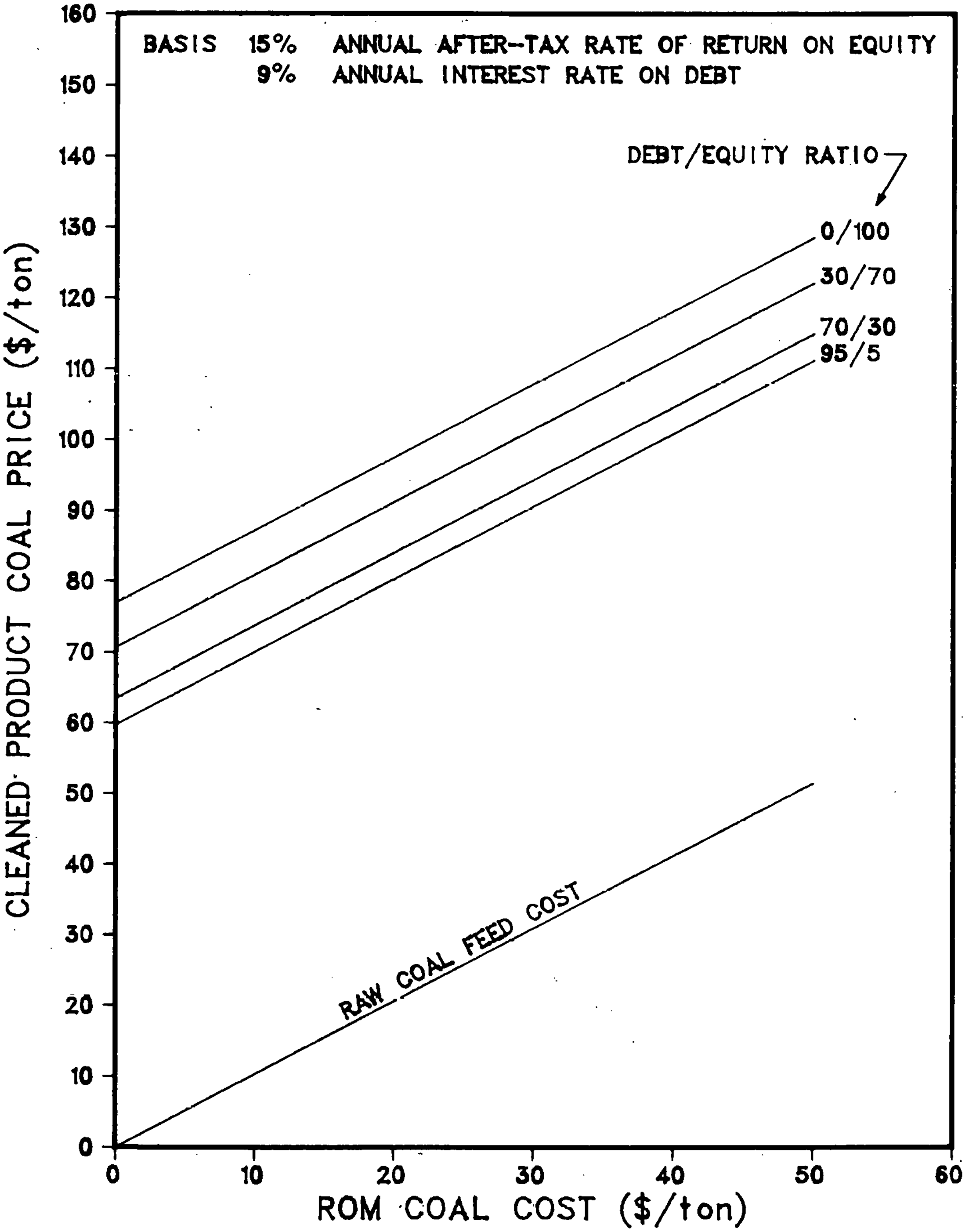


Fig. B-80. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

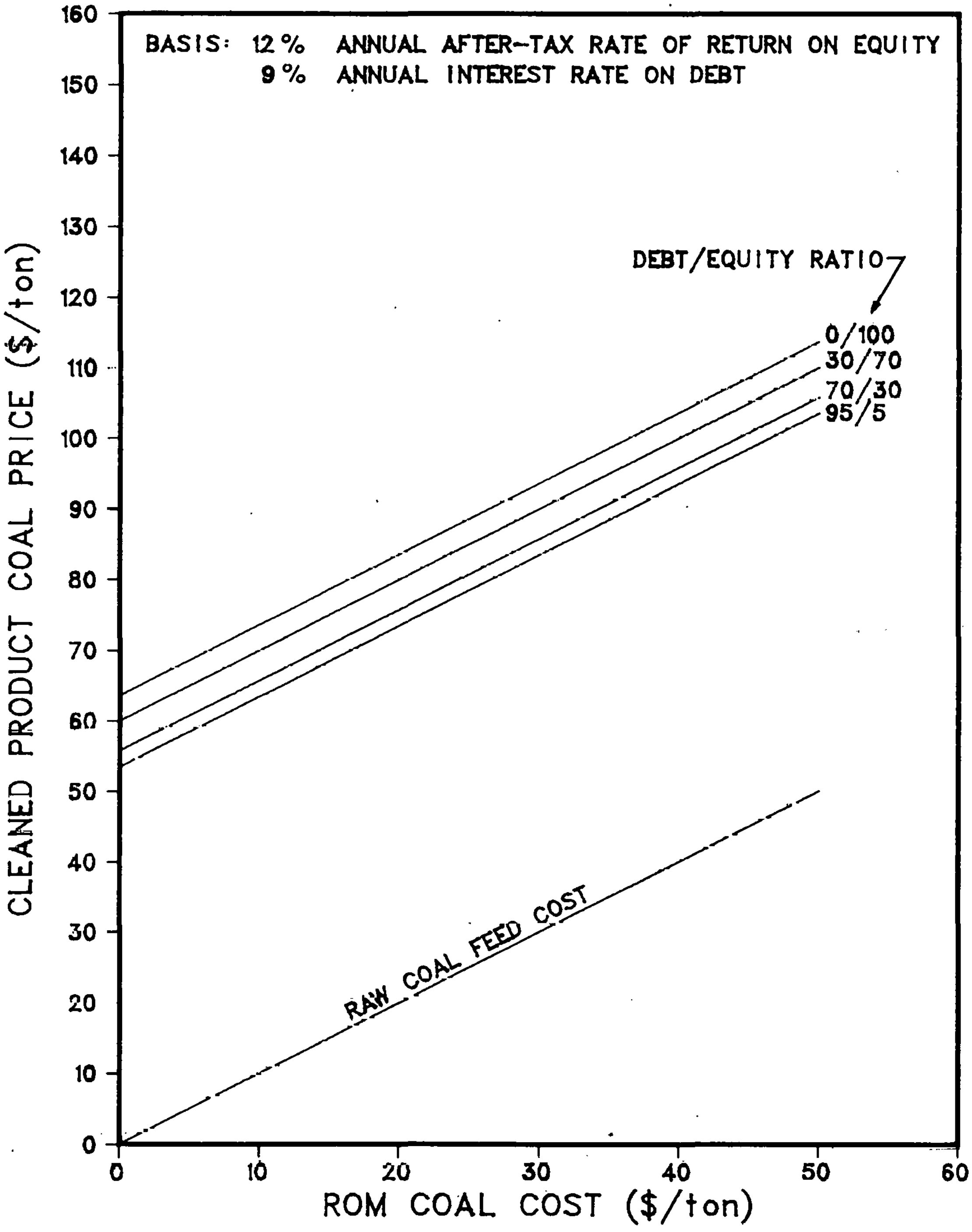


Fig. B-81. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

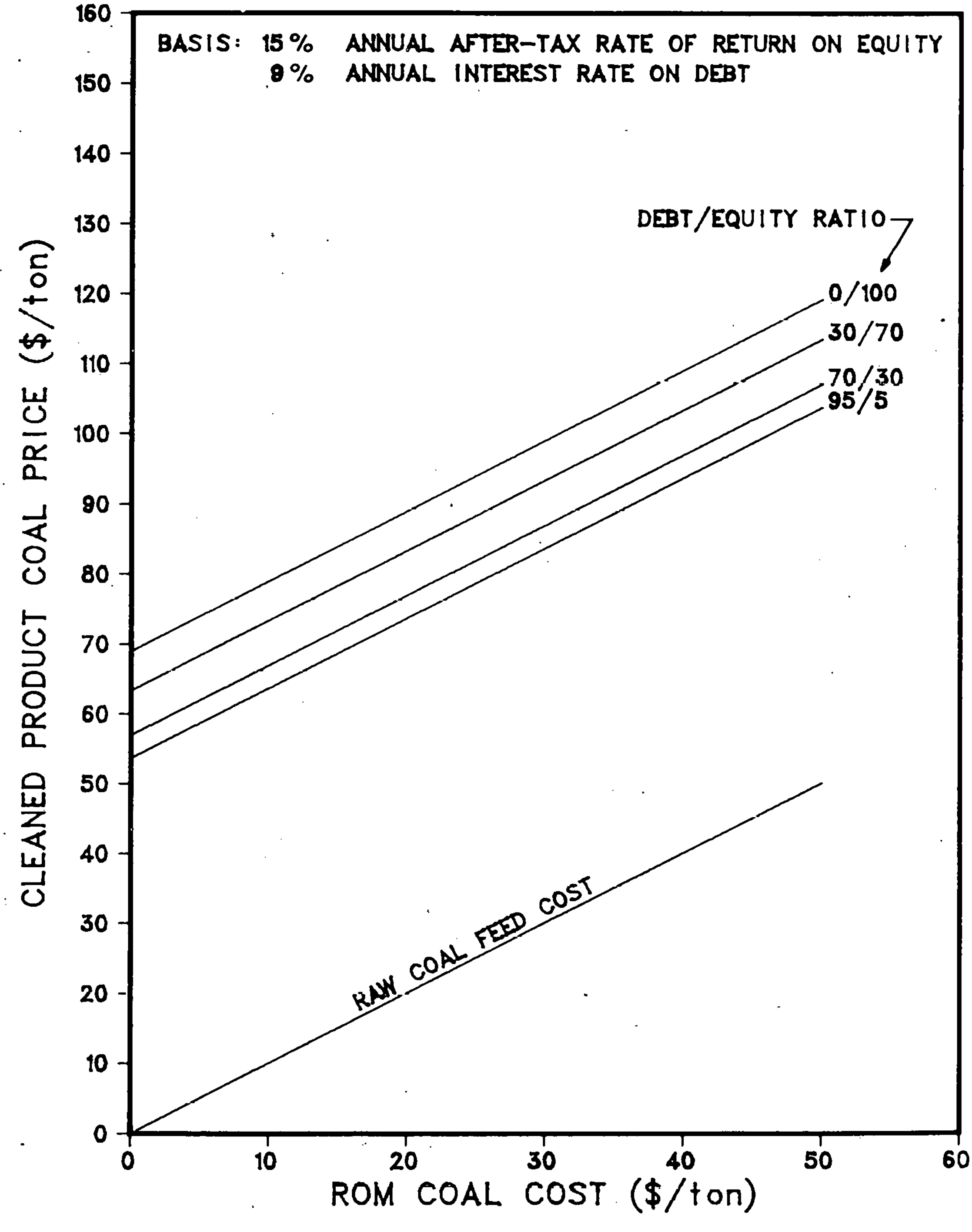


Fig. B-82. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

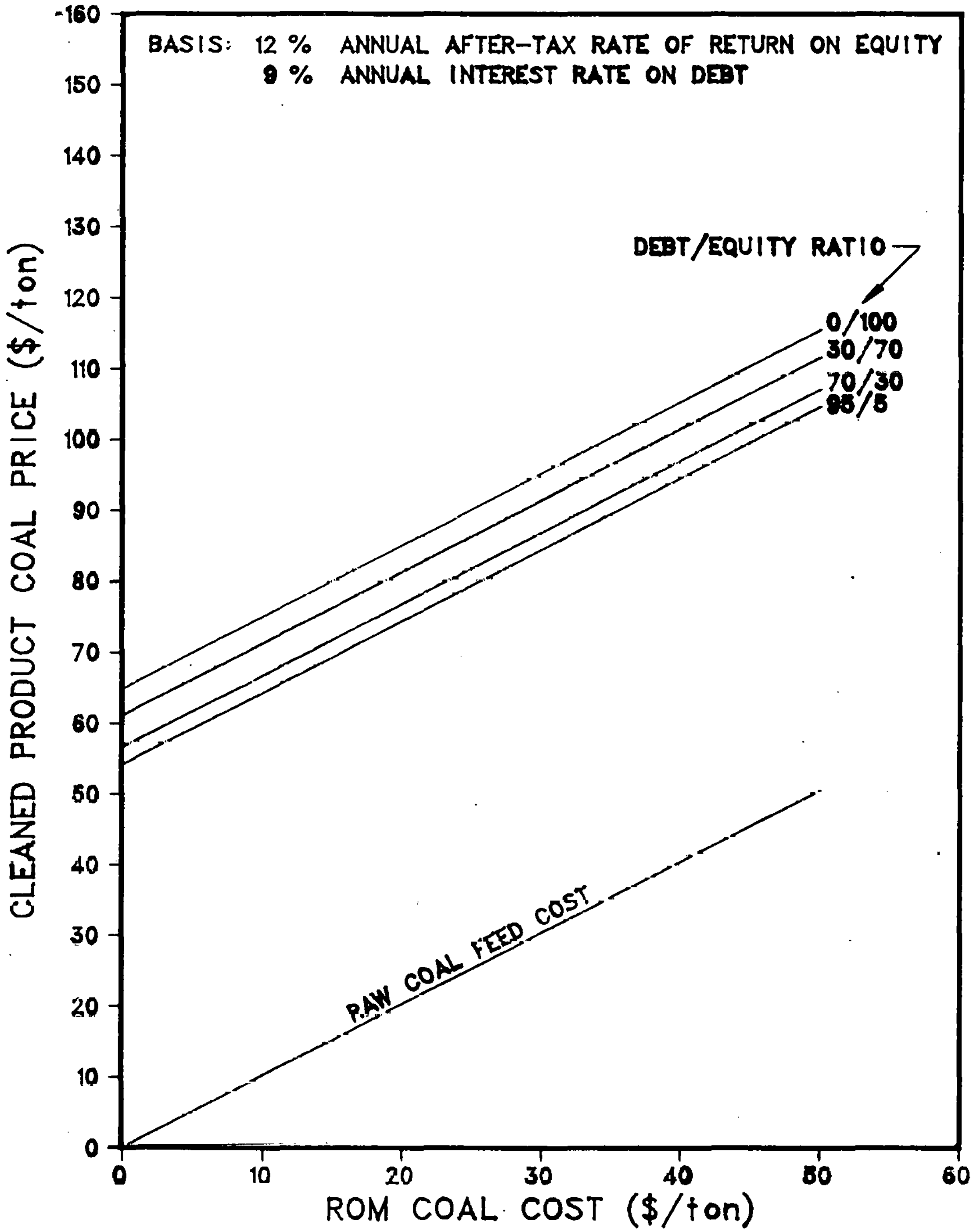


Fig. B-83. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

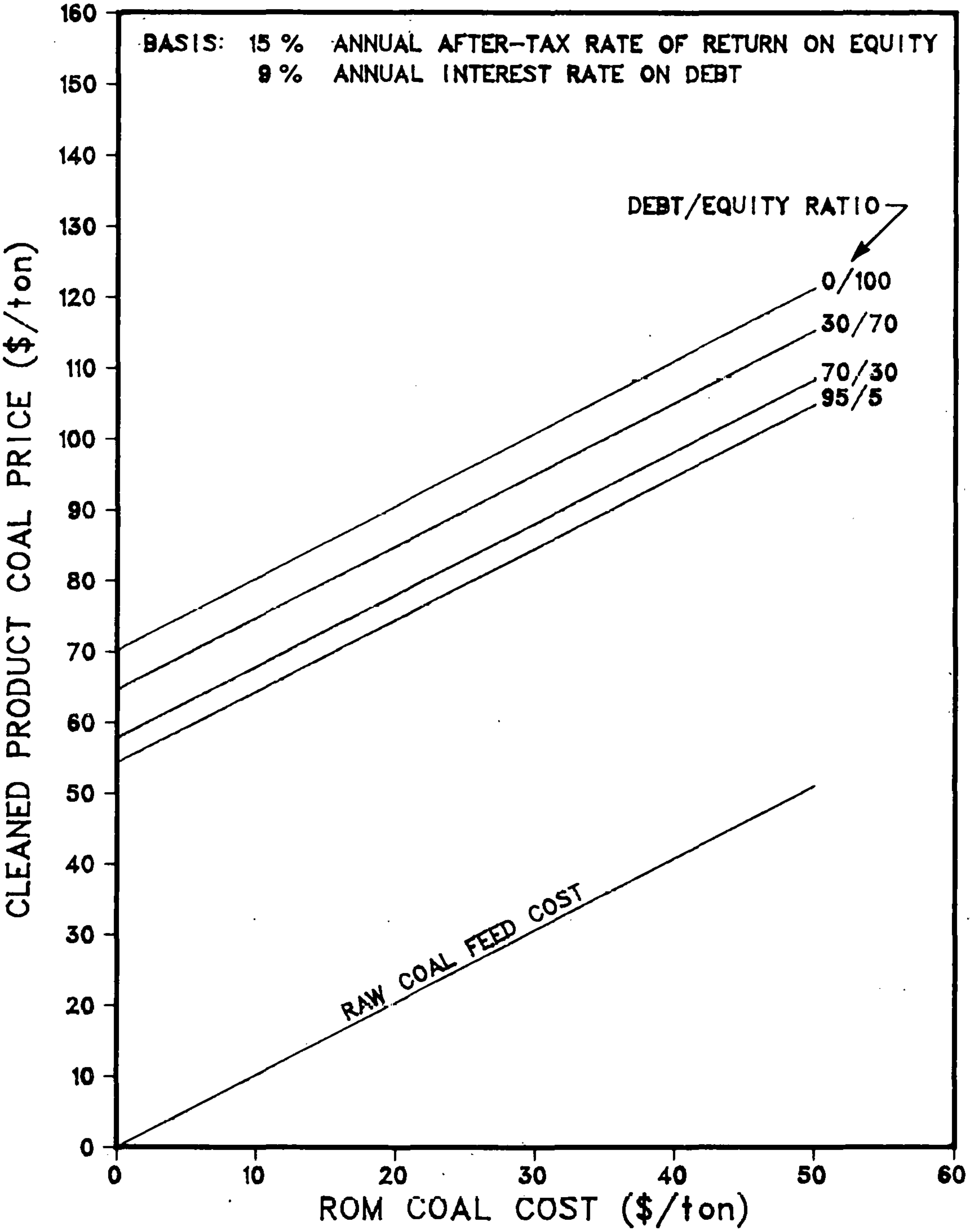


Fig. B-84. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 1500-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

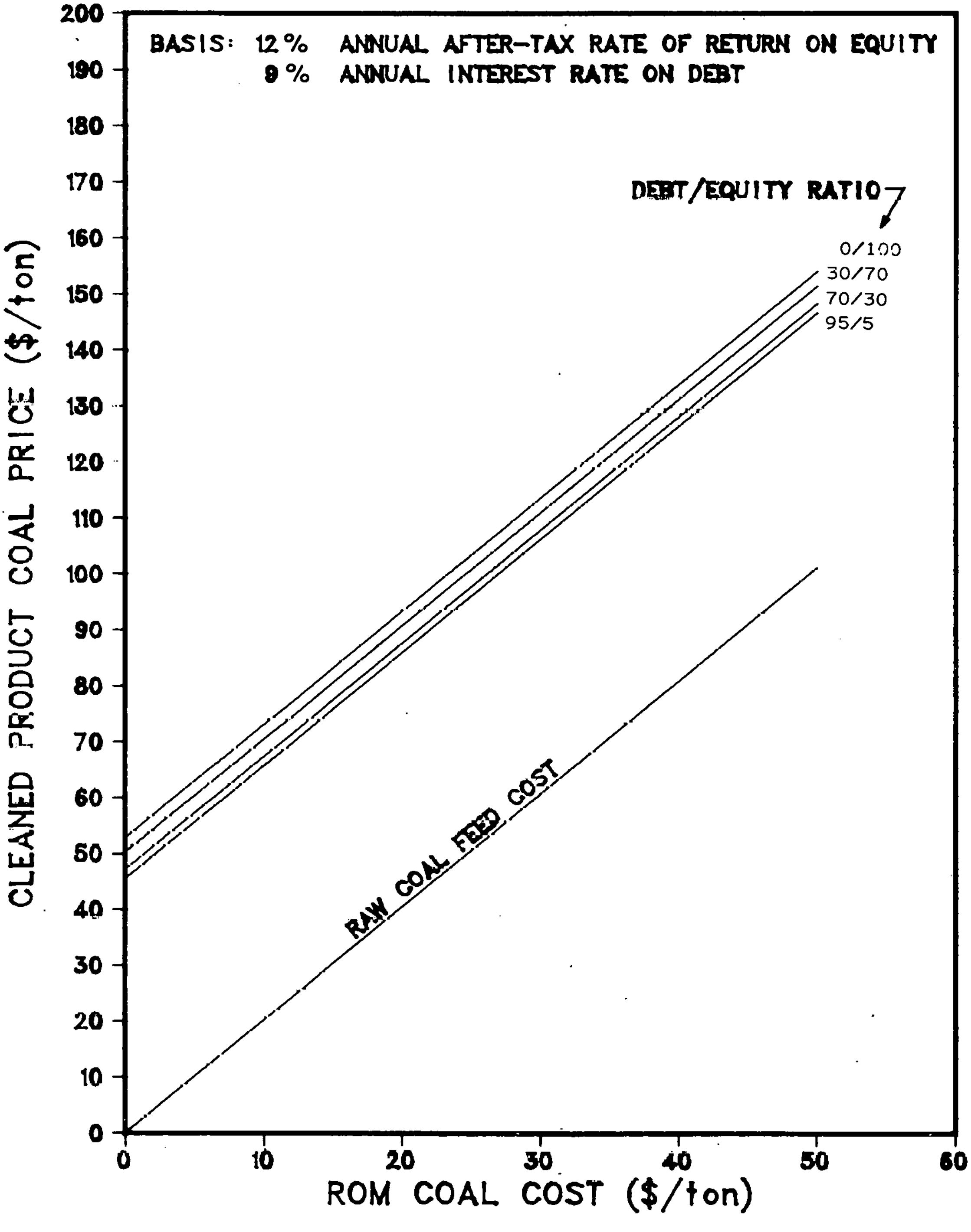


Fig. B-85. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 12% AARR on equity capital.

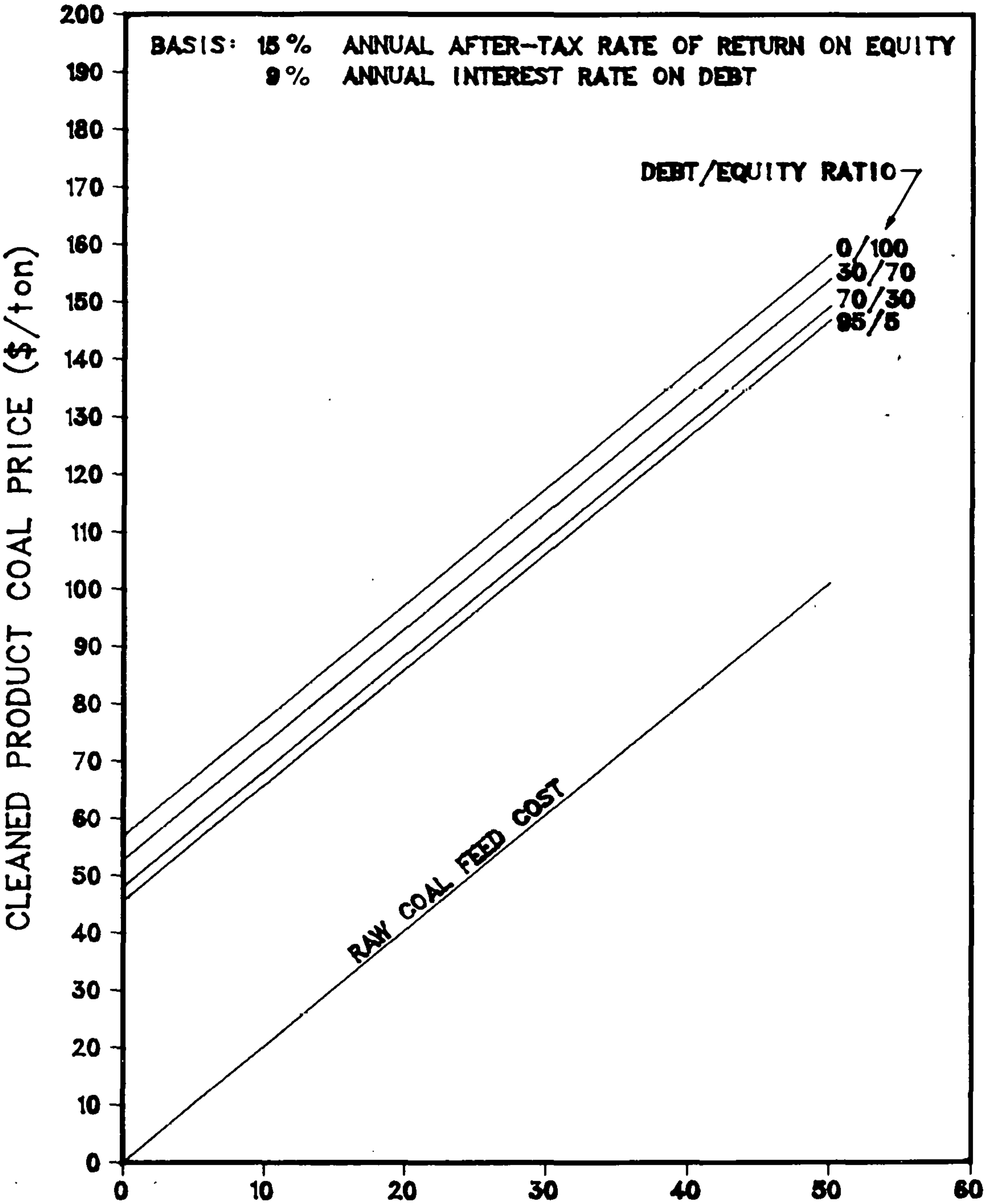


Fig. B-86. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Pennsylvania coal; grassroots facility; 15% AARR on equity capital.

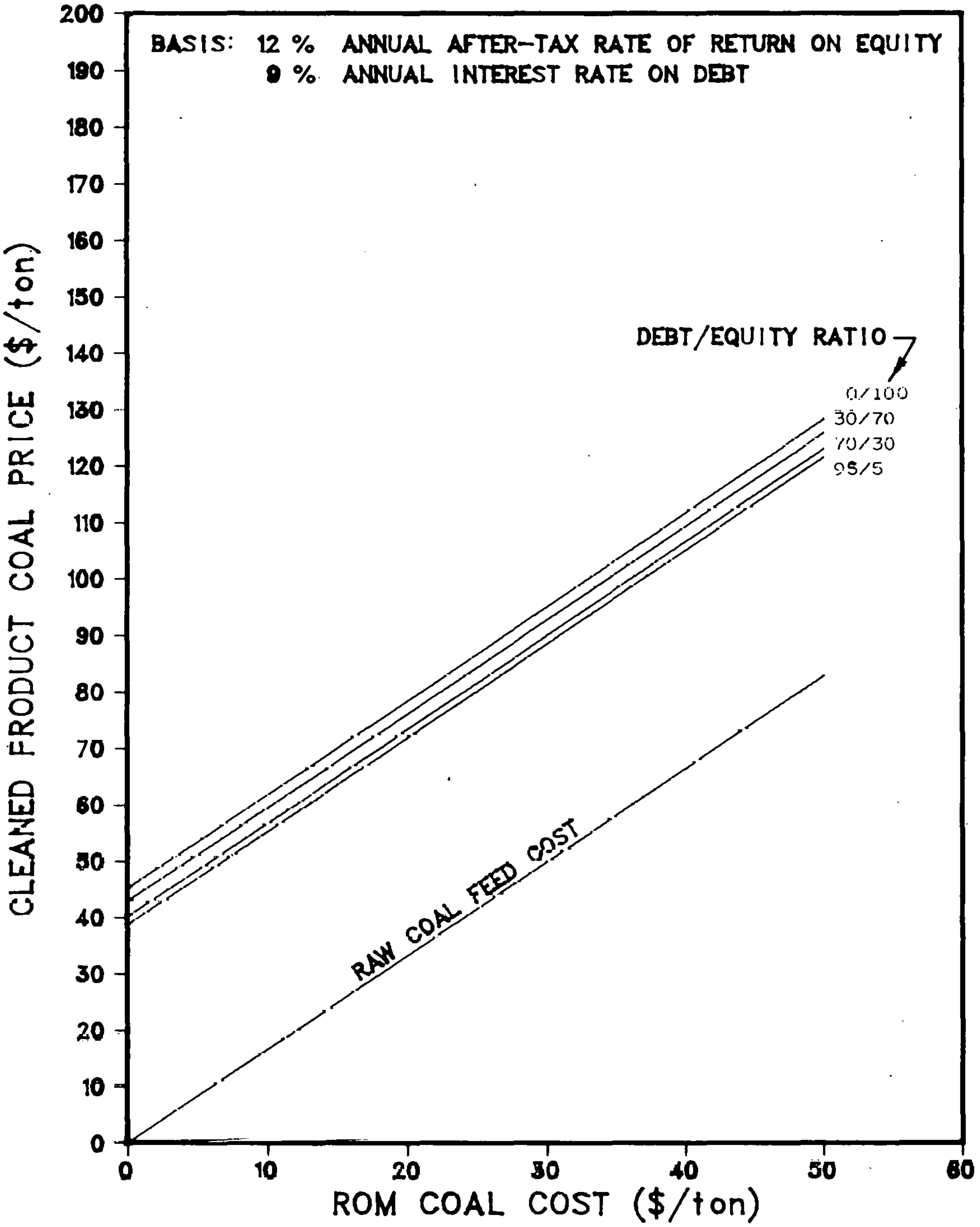


Fig. B-87. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 12% AARR on equity capital.

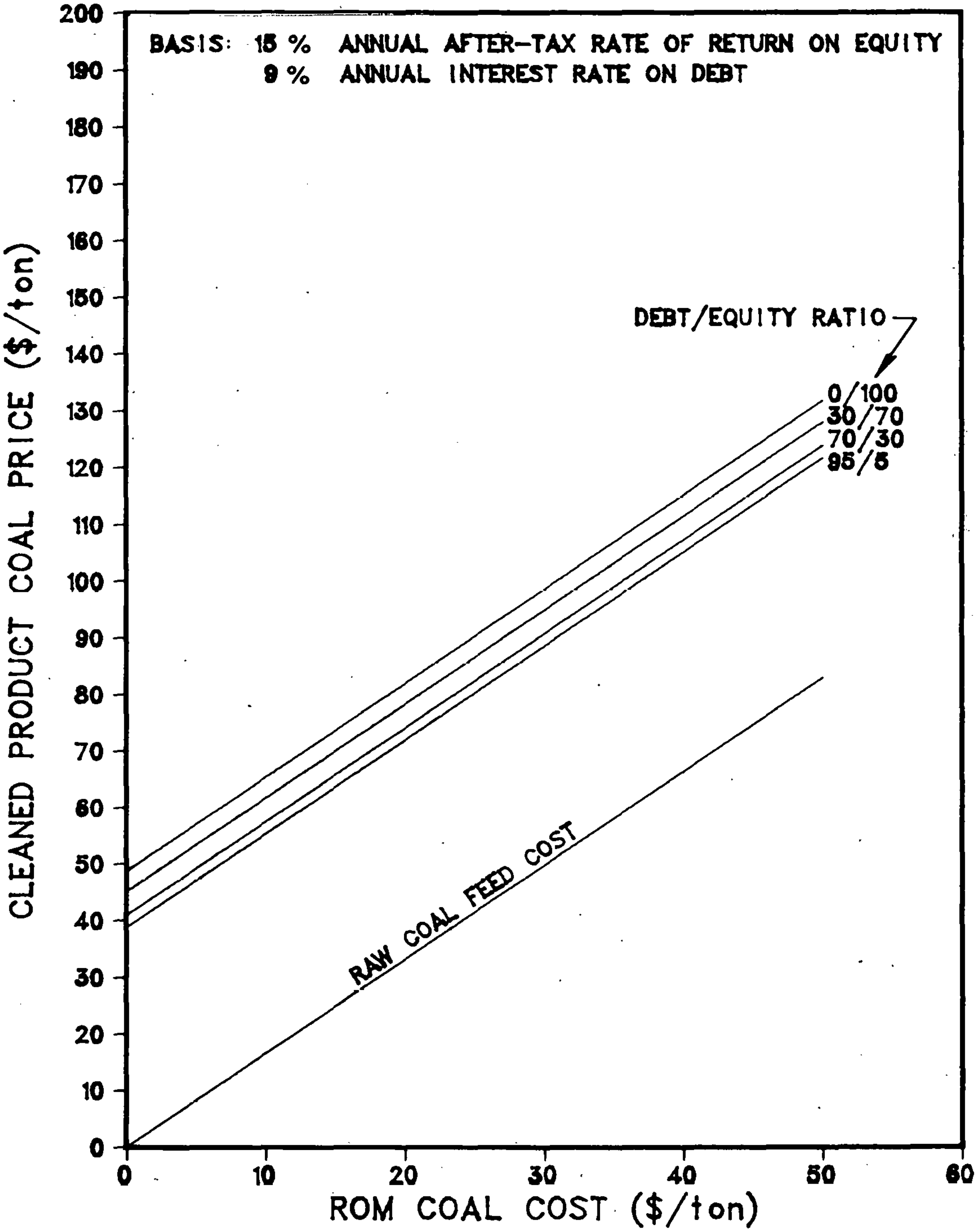


Fig. B-88. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; western Kentucky coal; grassroots facility; 15% AARR on equity capital.

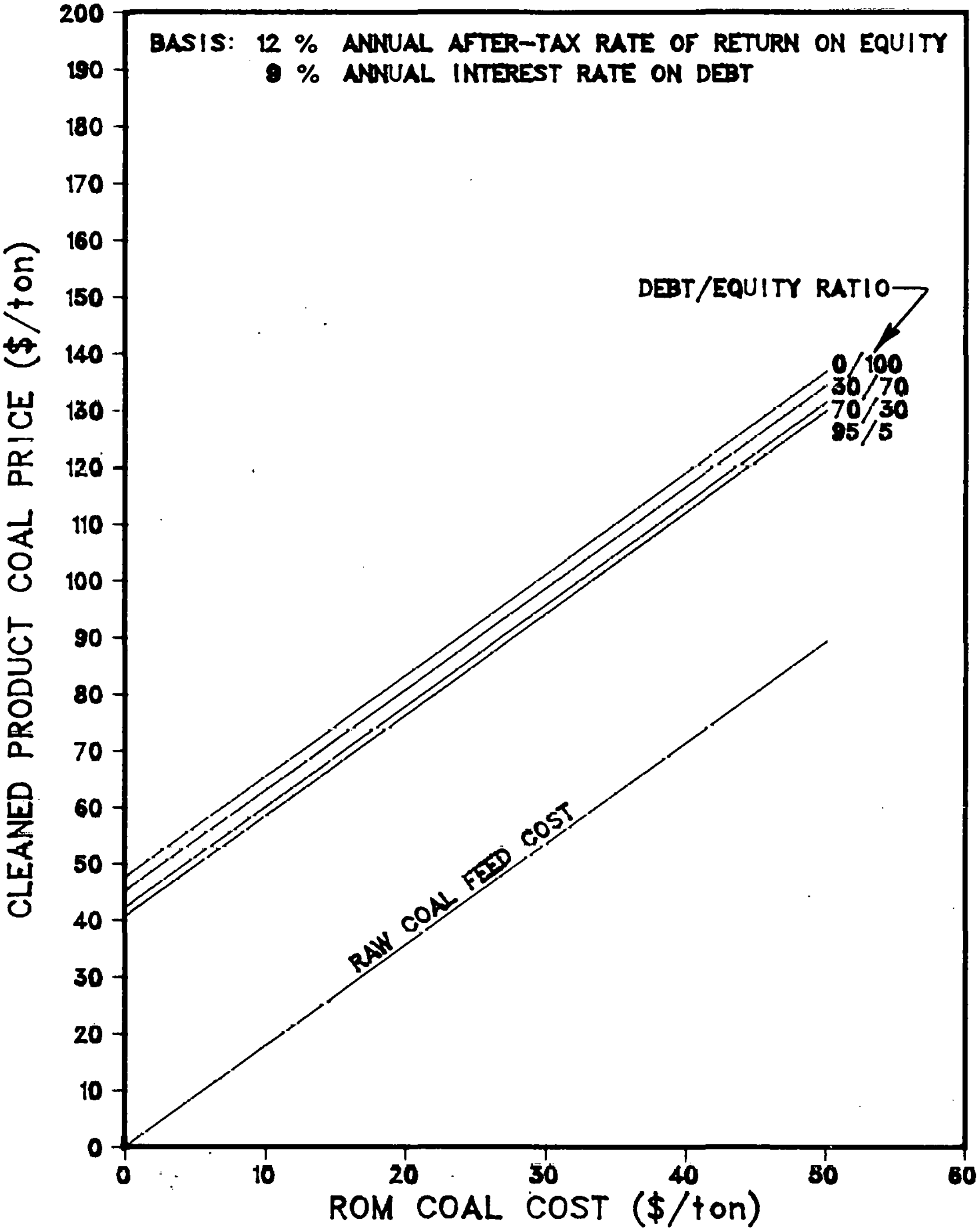


Fig. B-89. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Illinois coal; grassroots facility; 12% AARR on equity capital.

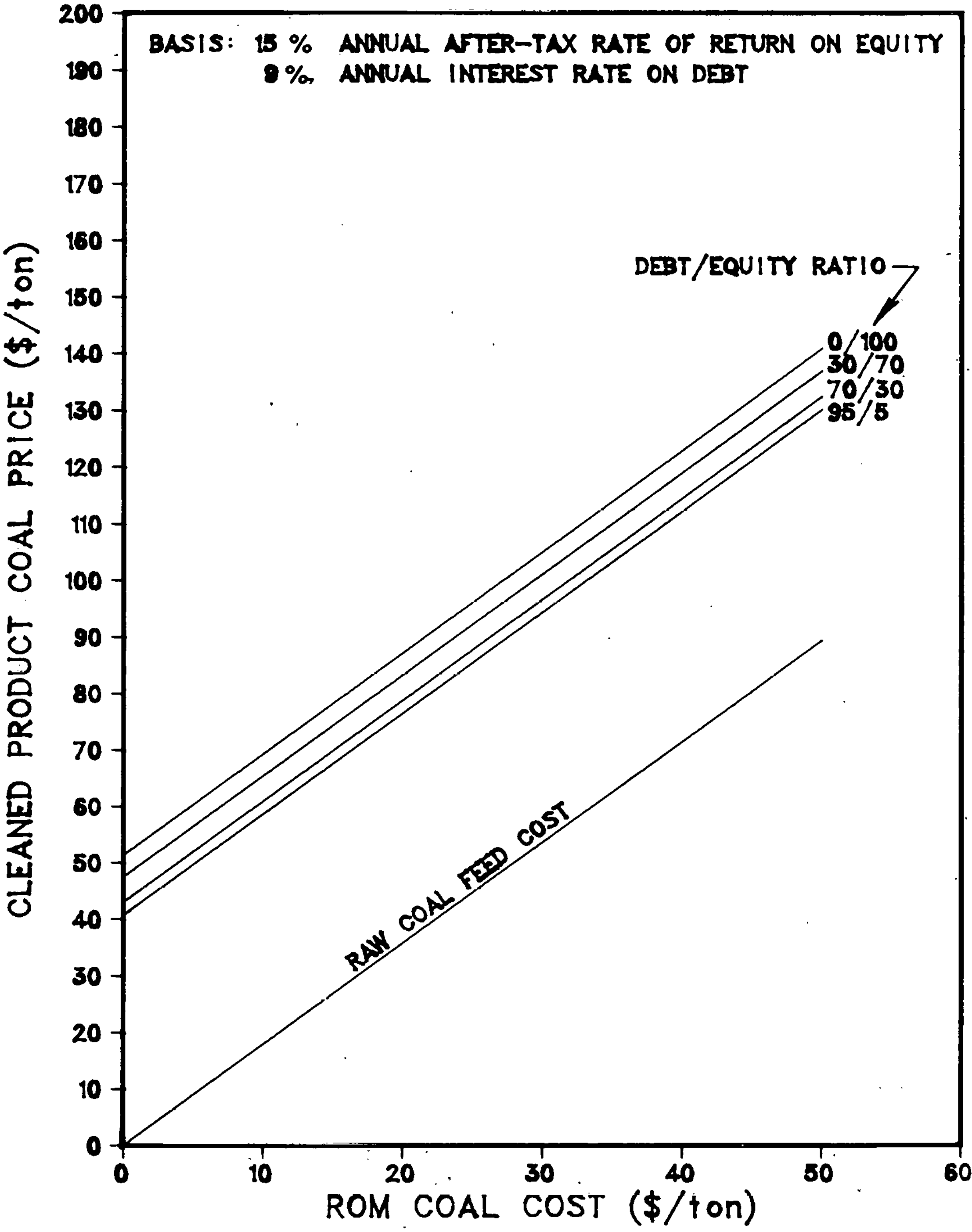


Fig. B-90. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Illinois coal; grassroots facility; 15% AARR on equity capital.

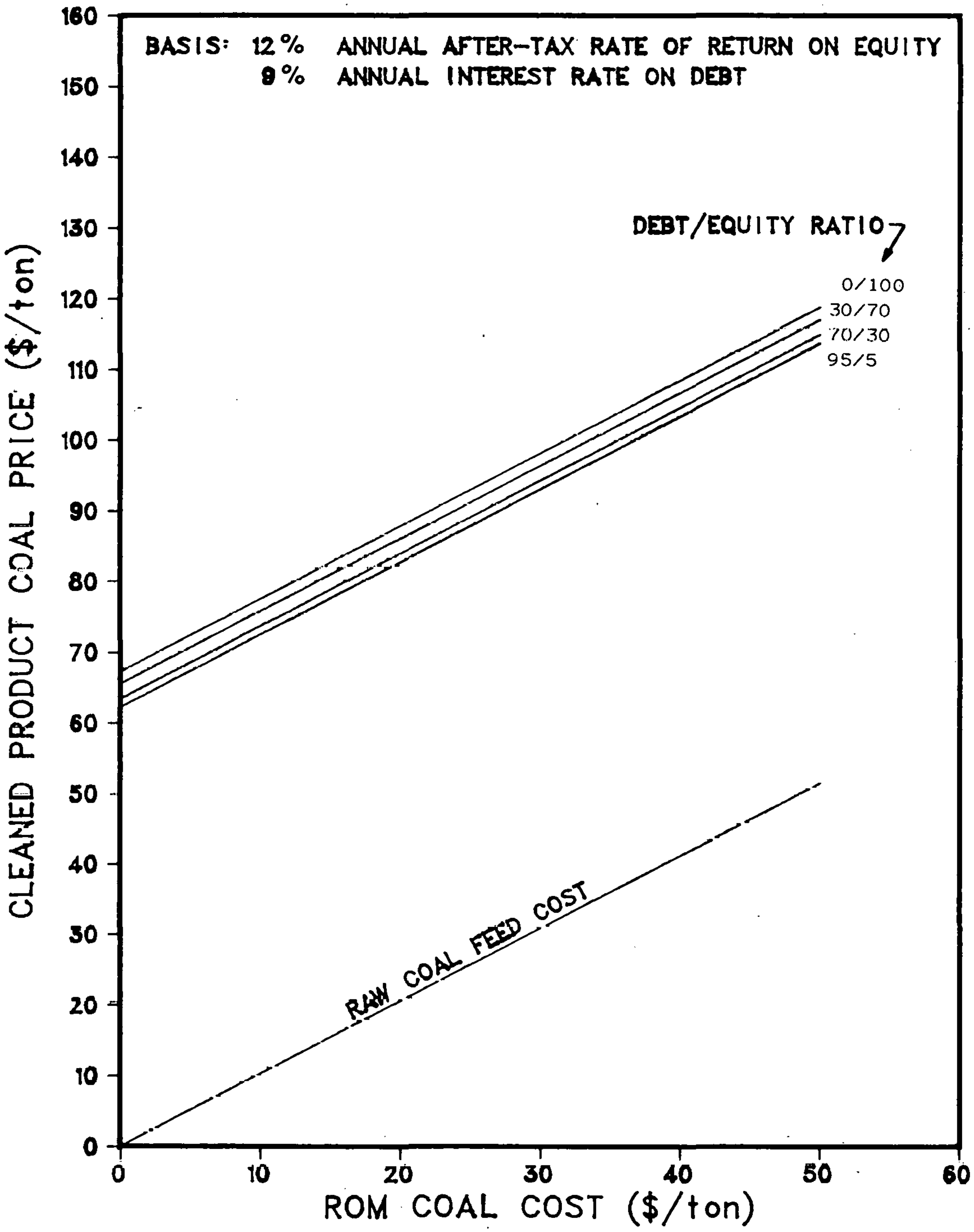


Fig. B-91. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 12% AARR on equity capital.

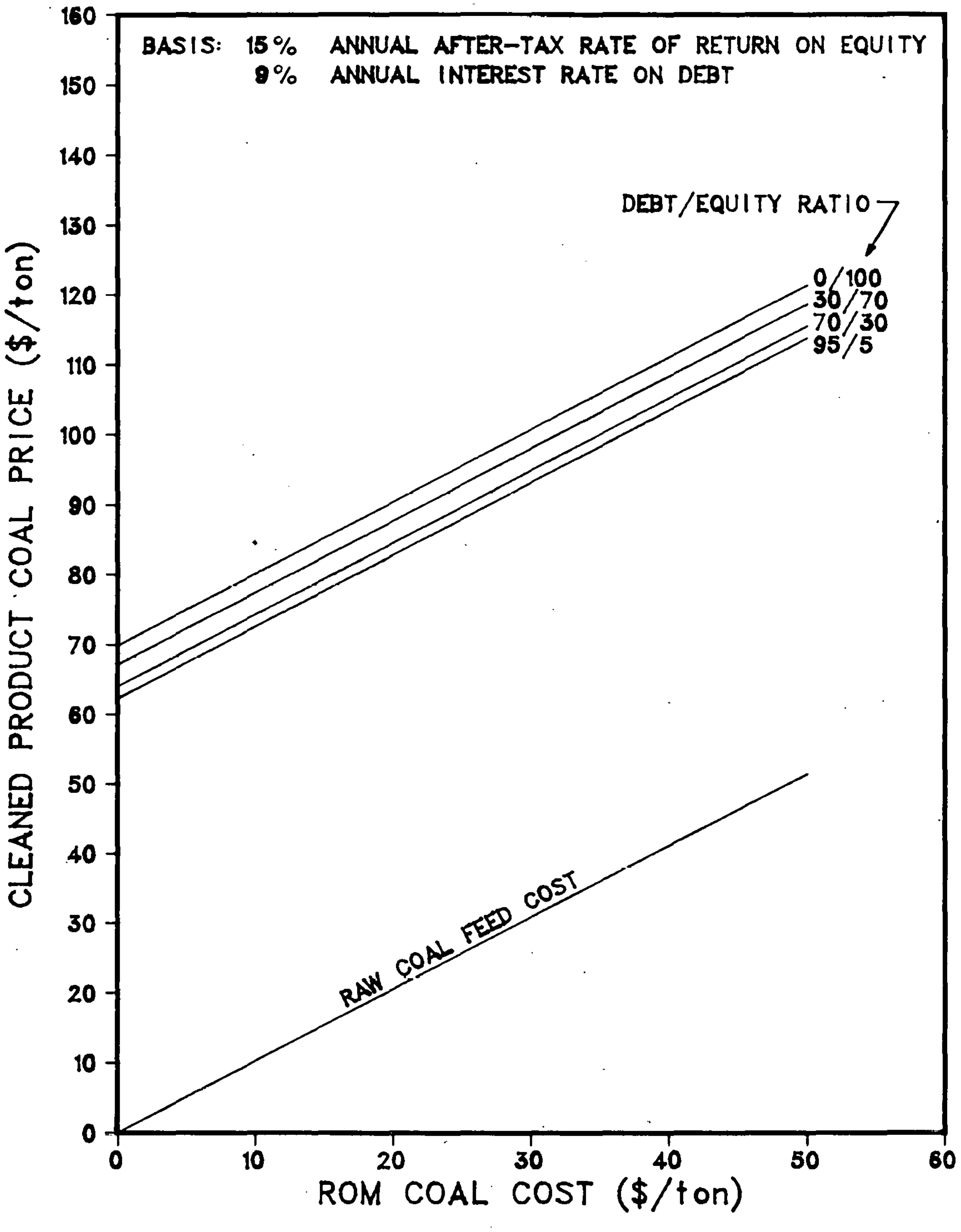


Fig. B-92. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Pennsylvania coal; battery-limits facility; 15% AARR on equity capital.

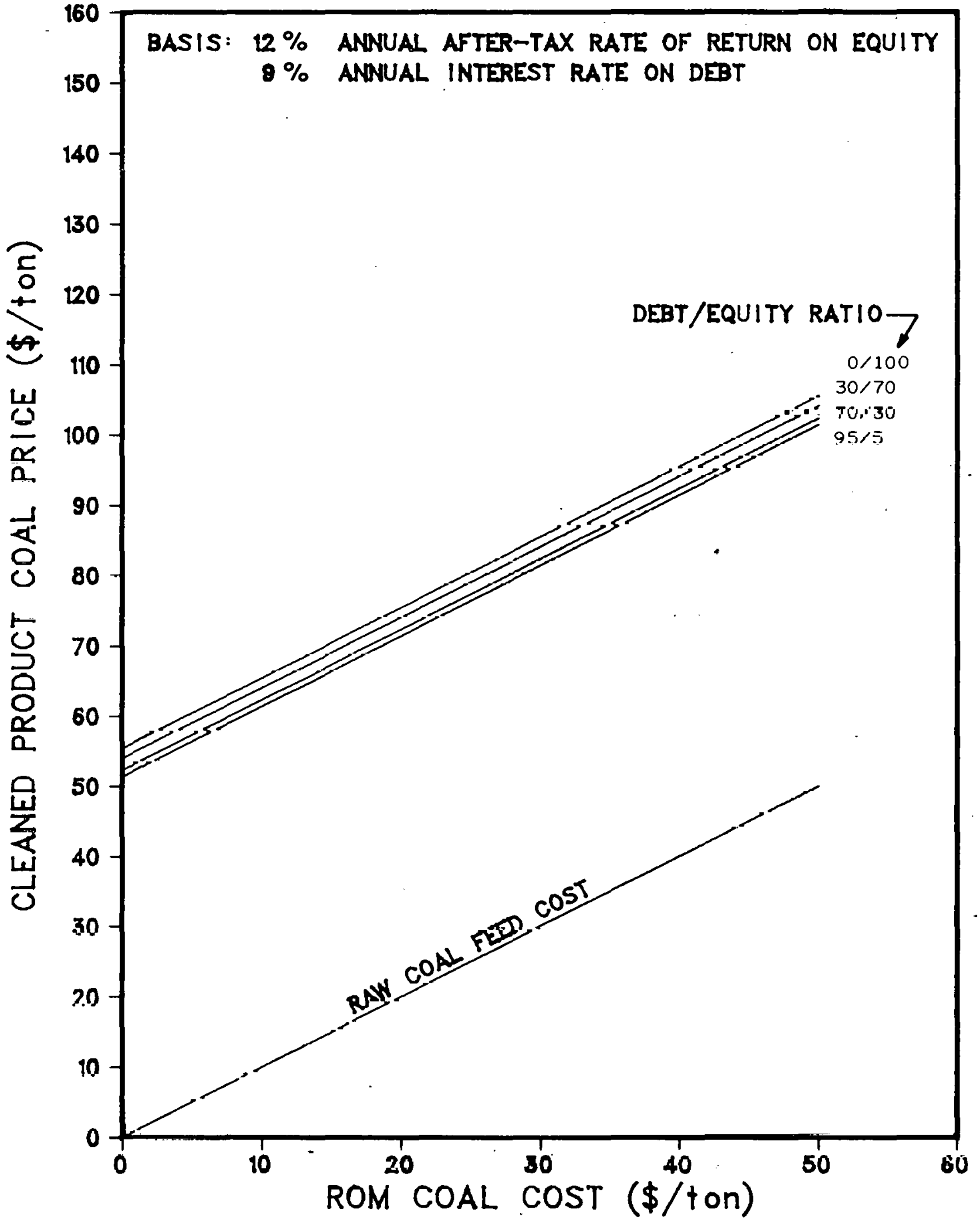


Fig. B-93. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 12% AARR on equity capital.

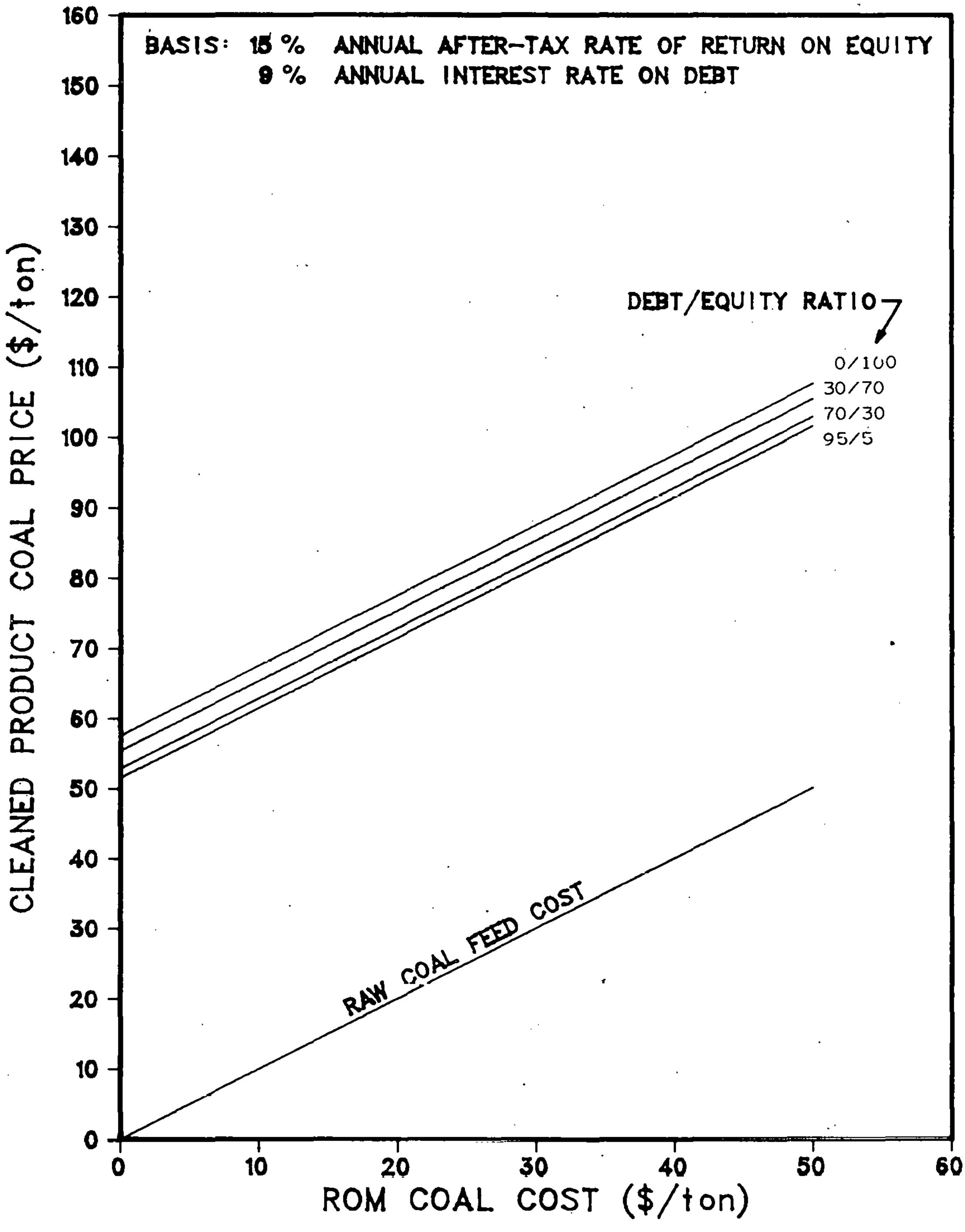


Fig. B-94. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; western Kentucky coal; battery-limits facility; 15% AARR on equity capital.

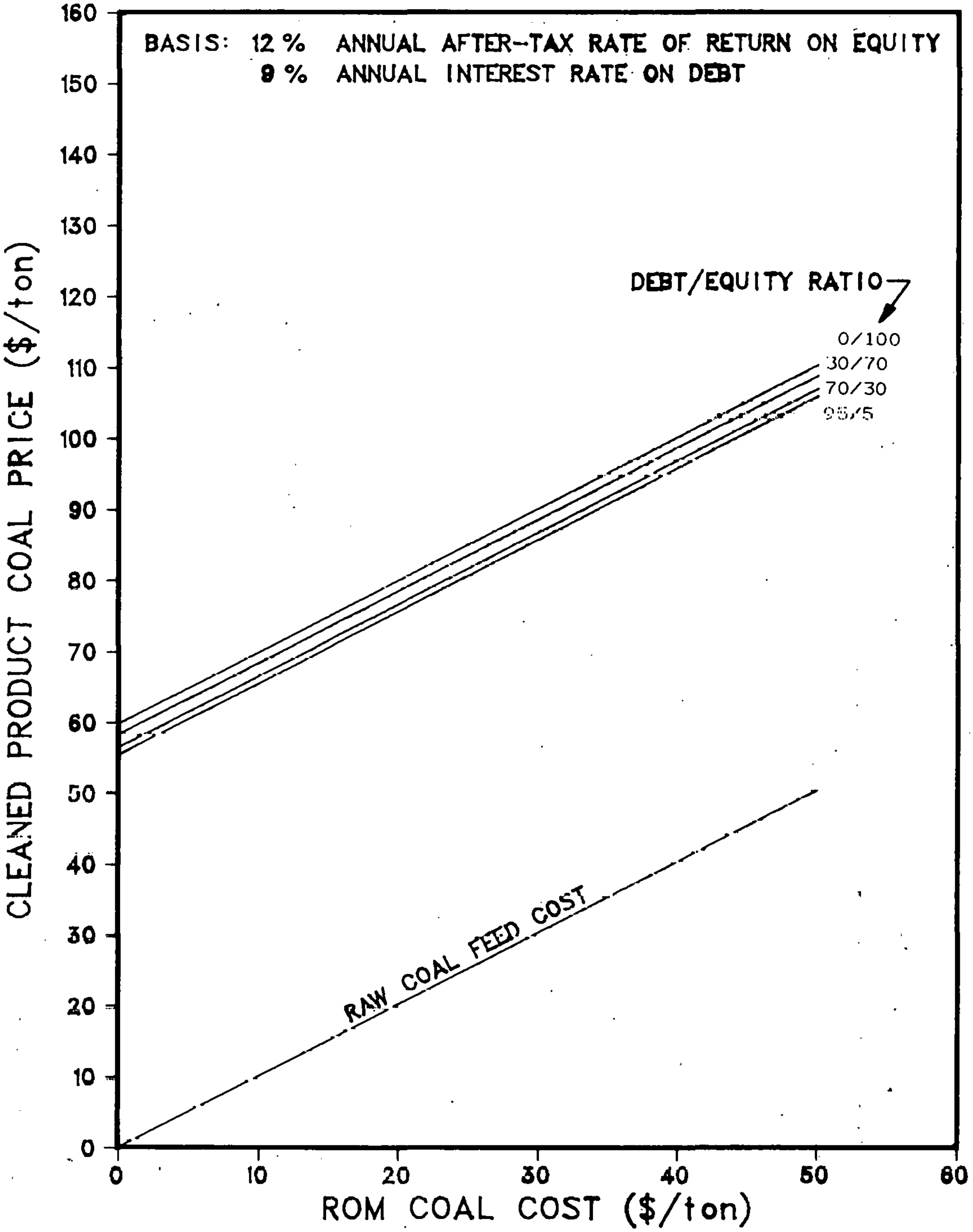


Fig. B-95. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Illinois coal; battery-limits facility; 12% AARR on equity capital.

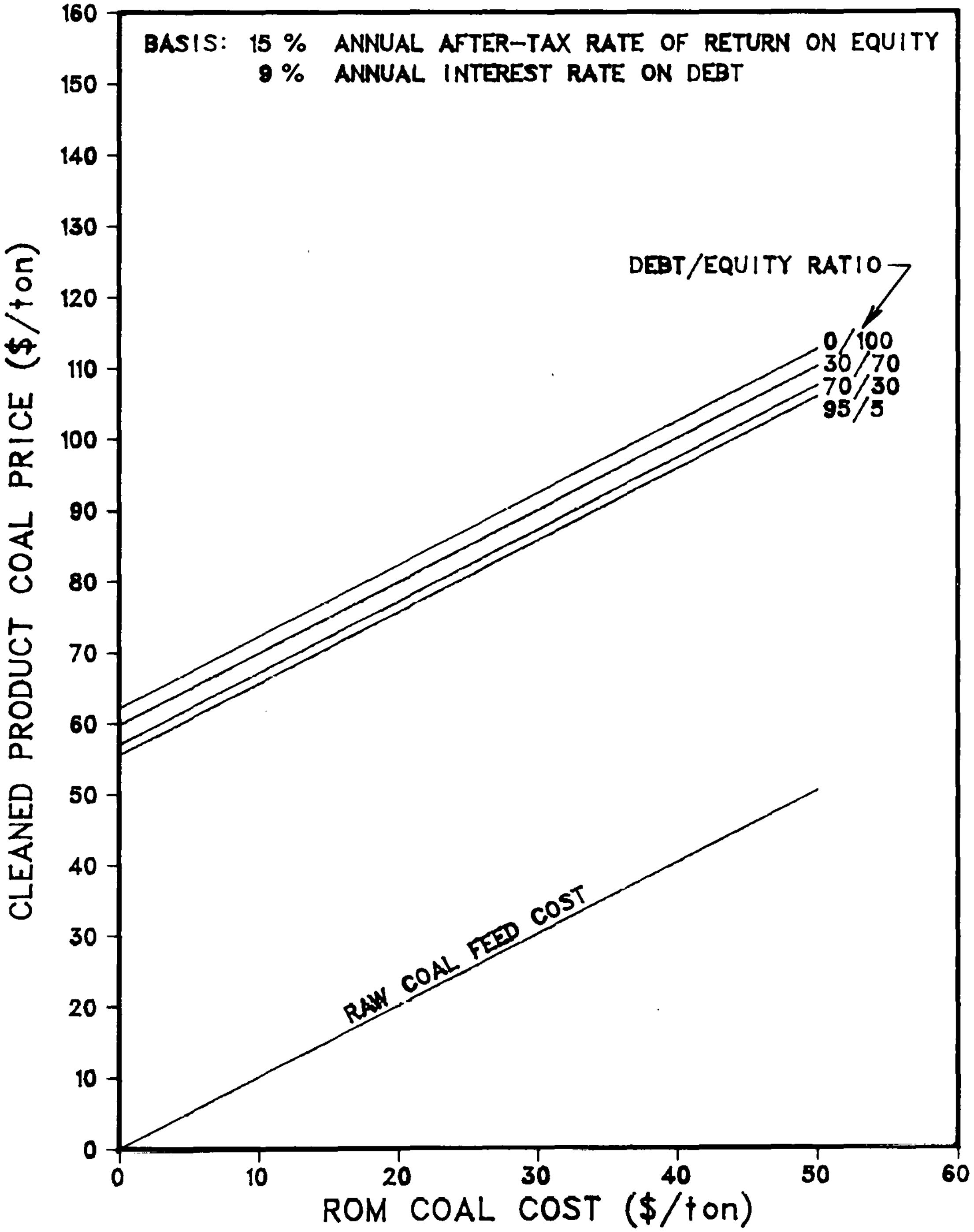


Fig. B-96. Cleaned product coal price for various ROM coal costs and debt/equity ratios. Parameters: BHCP; 15,000-ton/day plant; Illinois coal; battery-limits facility; 15% AARR on equity capital.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Appendix C: Equipment Lists for Some Beneficiation Processes Evaluated

Table C.1. Equipment list for a wet beneficiation mild-cleaning process at a 1500-ton/day facility (corresponds to Fig. 3.1)

Equipment No.	Quantity	Description
10-1701	1	ROM coal hopper
10-2301	2	Reciprocating feeder (150 tons/hr each)
10-2302	1	ROM coal transfer conveyor (300 tons/hr, 36-in. belt at 300 ft/min)
10-2501	1	5-ft-wide shaker screens
10-2401	1	9 x 17 ft rotary breaker
10-2303	1	Raw coal transfer conveyor (275 tons/hr, 30-in. belt at 300 ft/min)
10-2901	1	Self-cleaning magnet
10-2304	8	Vibrating feeder (40 tons/hr each)
10-2305	1	Wash plant feed conveyor
10-2801	1	Belt scales (275 tons/hr)
10-4002	1	Automatic sampling system (275 tons/hr)
11-2301	2	RC distribution conveyor (150 tons/hr each)
11-2501	4	Double-deck screen
11-4001	1	Jig washer (225 tons/hr)
11-2502	1	3-ft-wide drain and wash screen
11-2503	2	8 x 16 ft drain and wash screen
11-2201	1	Centrifuge (100 tons/hr)
11-3601	1	Fine coal sump
11-1501	2	Fine coal sump pump (1200 gal/min at 100 ft)
11-2302	1	Refuse collection conveyor (60 tons/hr, 24-in. belt at 100 ft/min)
11-2303	1	Refuse transfer conveyor (60 tons/hr, 24-in. belt at 100 ft/min)
11-1701	1	100-ton refuse bin with gate
11-1702	1	Water head tank
11-3701	3	Classifying cyclone (20-in.-diam)
11-2504	1	4-ft-wide cross-flow screen
11-2202	1	Centrifuge (5-10 tons/hr)
11-2304	1	Collection conveyor (160 tons/hr, 24-in. belt at 250 ft/min)

Table C.1 (continued)

Equipment No.	Quantity	Description
11-2305	1	Collection conveyor (10 tons/hr)
11-2306	1	Collection conveyor (60 tons/hr, 24-in. belt at 100 ft/min)
11-2307	1	Clean coal transfer conveyor (275 tons/hr, 30-in. belt at 300 ft/min)
11-4003	1	Automatic clean coal sampling kit
11-2308	1	Clean coal transfer conveyor (275 tons/hr, 30-in. belt at 300 ft/min)
11-2701	1	Refuse thickener (30-ft-diam)
11-1502	1	Clarified water pump (2500 gal/min at 90 ft)
11-1503	1	Thickener underflow pump (50 gal/min at 30 ft)
11-1504	1	Filter effluent pump (50 gal/min at 30 ft)
11-1505	1	Water seal booster pump (200 gal/min at 200 ft)
11-1901	1	Rotary vacuum disc filter with auxiliaries
11-2309	1	Refuse collection conveyor
	1	Air compressor and miscellaneous equipment (not shown)
12-1701	1	1700-ton clean coal silo with piling
12-2301	6	Feeder
12-2801	1	Undertrack scales
	1	Water supply and treatment unit
	1	Steam-electric power generation unit

Table C.2. Equipment list for a wet beneficiation mild-cleaning process at a 15,000-ton/day facility (corresponds to Fig. 3.2)

Equipment No.	Quantity	Description
10-1701	2	Receiving hopper with steel grates
10-2301	4	Reciprocating feeder (750 tons/hr each)
10-2302	2	ROM coal conveyor (1650 tons/hr each, 72-in. belt at 300 ft/min)
10-2501	2	10-ft-wide shaker screen
10-1501	2	Sump pump
10-2401	4	12 x 27 ft rotary breaker
10-1702	2	100-ton rock bin with grates
10-2303	2	Raw coal conveyor (1550 tons/hr, 60-in. belt at 350 ft/min)
10-2901	2	Self-cleaning magnet
10-2303	2	Raw coal transfer conveyor (1550 tons/hr, 60-in. belt at 350 ft/min)
10-2304	2	Yard conveyor (3000 tons/hr, 60-in. belt at 650 ft/min)
10-4001	2	Stacker-reclaimer with trailer and foundation
10-2305	1	Reversing transfer conveyor (2000 tons/hr, 60-in. belt at 450 ft/min)
10 1703	2	Raw coal silo with piling (3500 tons)
10-2306	2	Raw coal feeder (750 tons/hr)
10-2307	2	Washery feed conveyor (750 tons/hr, 36-in. belt at 500 ft/min)
10-2801	2	Belt scales
10-4002	2	Automatic raw coal sampler unit with all auxiliaries
11-2301	4	Distributing conveyor
11-2501	8	Raw coal screen (8 x 16 ft)
11-4001	2	Baum jig (625 tons/hr) with middlings crusher and rewasher
11-2502	2	7 ft x 16 ft screen
11-2503	4	8 ft x 16 in. double-deck drain and rinse screen

Table C.2 (continued)

Equipment No.	Quantity	Description
11-2201	4	Centrifuge
11-2302	2	Refuse collection conveyor 30-in. belt at 200 ft/min, 170 tons/hr
11-1701	1	Refuse bin (300 tons) with gate
11-3601	2	Fine coal sump
11-1501	4	Fine coal slurry pump (2850 gal/min at 750 ft)
11-1703	2	Water storage head tank
11-3761	16	20-in.-diam classifying cyclone
11-2504	4	4-ft-wide cross-flow screen
11-2202	2	Centrifuge (30 tons/hr)
11-1502	6	Clarified water pump (2000 gal/min at 100 ft)
11-1504	2	Pump seal booster pump (500 gal/min at 230 ft)
11-1503	1	Thickener underflow pump (200 gal/min at -60 ft)
11-1505	1	Filter effluent pump (100 gal/min at -60 ft)
12-4001	2	Automatic coal sampler (550 tons/hr)
12-2301	1	Sampled coal transfer conveyor (1100 tons/hr, 54-in. belt at 350 ft/min)
12-1701	1	15,000-ton concrete silo with piling (70 ft diam x 225 ft high)
12-2302	8	Vibrating feeder (450 tons/hr each) (not shown)
12-2303	1	Prepared coal loadout conveyor (3500 tons/hr, 72-in. belt at 500 ft/min)
12-4002	1	Loadout bin, tower, controls, auxiliaries
12-2802	1	Automatic under track scales
12-2801	1	Belt scales (3500 tons/hr)
12-2304	1	Boiler plant feed conveyor (20 tons/hr)
12-2802	1	Belt scales(20 tons/hr)

Table C.2 (continued)

Equipment No.	Quantity	Description
12-1702	1	Boiler plant feed coal storage bunker (100 tons)
11-2701	1	Slurry thickener
11-1901	1	Rotary vacuum disc filter and auxiliaries
11-2307	2	Clean transfer conveyor (550 tons/hr, 36-in. belt at 350 ft/min)
	2	Air compressor (not shown)
		Miscellaneous equipment
11-2306	2	Clean coal collection conveyor (350 tons/hr, 36-in. belt at 250 ft/min)
11-2309	2	RC transfer conveyor (750 tons/hr, 48-in. belt at 300 ft/min)
		(10-4002 to 11-2301 not shown)
11-2304	2	Collection conveyor (375 tons/hr, 36-in. belt at 250 ft/min)
11-2305	2	Collection conveyor (20 tons/hr)
11-2308	1	Filter cake scraper conveyor (20 tons/hr)
	1	Water supply and treatment unit
	1	Steam-electric power generation unit

Table C.3. Equipment list for a wet beneficiation deep-cleaning process at a 1500-ton/day facility (corresponds to Fig. 3.3)

Equipment No.	Quantity	Description
10-1701	1	ROM coal receiving hopper with steel grates
10-2301	1	Reciprocating feeder (425 tons/hr)
10-2302	1	ROM coal conveyor (425 tons/hr, 42-in. belt at 275 ft/min)
10-2501	1	5-ft-wide shaker screen
10-2401	1	9 x 17 ft rotary breaker
10-1702	1	100-ton rock bin with gate
10-2303	1	Raw coal conveyor (360 tons/hr, 36-in. belt at 350 ft/min)
10-2901	1	Self-cleaning magnet
11-2301	1	Raw coal feeder (360 tons/hr)
11-2302	1	Raw coal feed conveyor (360 tons/hr, 36-in. belt at 350 ft/min)
11-2801	1	Belt scales (360 tons/hr)
11-4001	1	Raw coal sampler system
11-2309	2	Distributing conveyor (180 tons/hr), (not shown)
11-2501	4	7-ft-wide cross-flow screen
11-2502	4	8 ft x 16 ft double-deck screen
11-1701	2	Head tank - 2-way cycloid
11-2901	4	Primary heavy-medium cycloid (28-in. diam)
11-1702	1	Fine coal sump
11-1501	1	Fine coal sump pump (3200 gal/min at 70 ft)
11-2503	2	7-ft-wide cross-flow screen
11-2504	2	8 ft x 16 ft drain and rinse screen
11-2505	1	5-ft-wide cross flow screen
11-2506	1	6 ft x 16 ft drain and rinse screen, double-deck
11-2201	2	Centrifuge
11-1703	1	Fine coal sump
11-1502	1	Fine coal slurry pump (130 gal/min at 40 ft)

Table C.3 (continued)

Equipment No.	Quantity	Description
11-1704	1	Primary heavy-medium recirculating sump
11-1506	2	Heavy-medium recirculating pump (300 gal/min at 60 ft)
11-2501	1	Crusher (30 tons/hr)
11-2507	1	4 ft x 12 ft drain and rinse screen
11-1705	1	Secondary heavy-medium feed pump
11-1503	1	Slurry feed pump (2100 gal/min at 90 ft, sp gr 1.9)
11-2902	2	20-in.-diam heavy-medium cycloid
11-2508	1	3-ft-wide cross-flow screen
11-2509	1	4 ft x 12 ft drain and rinse screen
11-2510	1	6-ft-wide cross-flow screen
11-2511	1	7 ft x 16 ft drain and rinse screen
11-2701	1	35-ft-diam dilute-medium clarifier
11-1504	1	Clarified water pump (1260 gal/min at 70 ft)
11-1505	1	Clarifier underflow pump (1680 gal/min at 80 ft, sp gr 1.2)
11-2903	3	Double-drum magnetic separator (30 in. diam x 108 in. long with distributors)
11-1707	1	Magnetite storage bin
11-2304	1	Magnetite screw feeder
11-1706	1	Heavy-medium storage sump with recirculating pump
11-2305	1	Refuse collection conveyor
11-2306	1	Refuse transfer conveyor
11-1708	1	Refuse collection bin (100 tons with gate)
11-2303	1	Clean coal collection conveyor (225 tons/hr, 36-in. belt at 150 ft/min)
11-3701	4	20-in.-diam classifying cyclone
11-4003	2	3-cell froth flotation (66 x 66 in.)
11-1709	1	Water tank

Table C.3 (continued)

Equipment No.	Quantity	Description
11-1901	1	Rotary vacuum disc filter with auxiliaries (11 ft diam with 10 discs)
11-1902	1	Rotary vacuum disc filter with auxiliaries (8 ft diam with 7 discs)
11-1507	1	Effluent pump (530 gal/min at 20 ft)
11-1508	1	Effluent pump (5375 gal/min at 20 ft)
11-2307	1	Filter cake distributing conveyor
11-2308	1	Filter cake transfer conveyor (30 tons/hr, 24-in. belt at 100 ft/min)
11-2702	1	Thickener (15 ft diam)
11-1509	1	Scrubber feed pump (350 gal/min at 80 ft)
11-1511	1	Thickener underflow pump (15 gal/min at 50 ft)
11-1510	1	Pump (3500 gal/min at 80 ft)
11-1512	1	Pump (375 gal/min at 70 ft)
12-2302	1	Clean coal conveyor (225 tons/hr, 30-in. belt at 300 ft/min)
12-2601	1	Dryer with all auxiliaries and scrubber (12-2101)
12-2303	1	Dried coal transfer conveyor (30 tons/hr, 24-in. belt at 100 ft/min)
12-4001	1	Clean coal sampling system (250 tons/hr)
12-2303	1	Clean coal transfer conveyor (250 tons/hr, 30-in. belt at 350 ft/min)
12-2801	1	Belt scales (1000 tons/hr)
12-1701	1	1500-ton dry coal silo with piling
12-2304	1	Feeder (1000 tons/hr)
12-4002	1	Car haul
	1	Steam-electric power generation unit
	1	Water treatment unit

Table C.4. Equipment list for a wet beneficiation deep-cleaning process at a 15,000-ton/day facility (corresponds to Fig. 3.4)

Equipment No.	Quantity	Description
10-1701	2	Receiving hoppers with steel grates
10-2301	4	Reciprocating feeder (750 tons/hr each)
10-2302	2	ROM coal conveyor (1650 tons/hr each, 72-in. belt at 300 ft/min)
10-2501	2	10-ft-wide shaker screen
10-1501	2	Sump pump
10-2401	4	12 x 27 ft rotary breaker
10-1702	2	100-ton rock bin with gates
10-2303	2	Raw coal conveyor (1550 tons/hr, 60-in. belt at 350 ft/min)
10-2901	2	Self-cleaning magnet
10-2303	2	Raw coal transfer conveyor (1550 tons/hr, 60-in. belt at 350 ft/min)
10-2304	2	Yard conveyor (3000 tons/hr, 60-in. belt at 650 ft/min)
10-4001	2	Stacker - reclaimer with trailer and foundation
10-2305	1	Reversing transfer conveyor (2000 tons/hr, 60-in. belt at 450 ft/min)
10-1703	2	Raw coal silo with piling (3500 tons)
10-2306	2	Raw coal feeder (750 tons/hr)
10-2307	2	Washery feed conveyor (750 tons/hr, 36-in. belt at 500 ft/min)
10-2801	2	Belt scales
10-4002	2	Automatic raw coal sampler unit with all auxiliaries
11-2501	12	7-ft-wide cross-flow screen
11-2502	12	8 ft x 16 ft desliming screens
11-1701	7	Two-way head tanks
11-2901	13	28-in.-diam heavy-medium cycloid
11-2503	7	7-ft-wide cross-flow screen
11-2504	7	8 ft x 16 ft drain and rinse screen
11-2201	5	Centrifuge

Table C.4 (continued)

Equipment No.	Quantity	Description
11-2505	4	7-ft cross-flow screen
11-2506	4	8 ft x 12 ft drain and rinse screen
11-2401	2	Crusher
11-2507	2	4 ft x 8 ft drain and rinse screen
11-2702	2	Cyclone feed sump
11-1501	4	Cyclone feed pumps
11-1703	4	Heavy-medium recirculating sump
11-1506	6	Heavy-medium recirculating pump
11-1704	2	Centrifuge drain sump
11-1502	2	Pump (500 gal/min, 45 psi)
11-1705	2	Secondary feed sump
11-1503	2	Secondary feed pump (4500 gal/min, 60 psi)
11-1706	2	Magnetic slurry head tank with pump
11-1707	2	Magnetite storage bin
11-2304	2	Screw feeder
11-2902	4	28-in.-diam cycloid
11-2508	2	4-ft-wide cross-flow screen
11-2509	2	5 ft x 12 ft drain and rinse screen
11-2202	2	Centrifuge
11-2510	4	5-ft-wide cross-flow screen
11-2511	4	6 ft x 16 ft drain and rinse screen
11-2305	2	Refuse collection conveyor
11-2306	2	Refuse conveyor
11-2903	6	Magnetite separator
11-2701	2	Dilute medium clarifier
11-1504	2	Clarifier overflow pump
11-1505	2	Clarifier underflow pump

Table C.4 (continued)

Equipment No.	Quantity	Description
11-1708	1	Refuse hopper with gate
11-3701	10	Cyclone (20 in. diam)
	2	Water storage tank
11-4003	12	Froth flotation cell, four banks of three cells each
11-1901	4	Disc filter with auxiliaries
11-1902	2	Disc filter with auxiliaries
11-1507	1	Filtrate pump
11-1508	1	Filtrate pump
11-2307	2	Filter cake collection conveyor
11-2309	2	Refuse cake collection conveyor
11-2310	2	Refuse transfer conveyor
11-2303	2	Clean coal collection conveyor (450 tons)
11-2308	2	Fine coal transfer conveyor
12-4001	2	Automatic coal sampler
12-2302	2	Clean coal transfer conveyor (500 tons/hr)
12-2301	2	Clean coal transfer conveyor (500 tons/hr)
12-2304	1	Clean coal boiler plant conveyor (100 tons/hr)
12-2305	1	Dry clean coal transfer conveyor (100 tons/hr) (not shown)
12-1701	1	15,000-ton silo with piling
12-2306	8	Vibrating feeder
12-2307	1	Loadout coal conveyor (3500 tons/hr)
12-2801	1	Belt scales(3500 tons/hr)
12-2802	1	Belt scales(100 tons/hr)
12-4002	1	Product coal loadout bin, tower, controls with auxiliaries
12-2803	1	Undertrack scale (automatic)
12-2601	2	Coal dryer
12-2101	2	Coal dryer flue-gas scrubber
	1	Steam and electric power generation unit
	1	Water supply and treatment unit

Table C.5. Equipment list for Battelle hydrothermal coal process (15,000-ton/day facility)

Quantity	Description
2	Receiving hopper with steel grates
4	Reciprocating feeder
2	ROM coal conveyor
2	Shaker screener
2	Sump pump
4	Rotary breaker
2	Rock bin with gates
2	Raw coal conveyor
2	Self-cleaning magnet
3	Raw coal transfer conveyor
3	Yard conveyor
3	Stacker/reclaimer with trailers
2	Reversing conveyor
3	Raw coal silo
3	Raw coal feeder
3	Ball mill feed conveyor
3	Belt scales
3	Automatic raw coal sampling unit
3	Raw coal distributing conveyor
12	Wet ball mill with all auxiliaries
5	Mixing and preheat vessel with agitators, drives, and heating system
1	Caustic receiving hopper with feeder
1	Transfer conveyor
1	Caustic storage bin
5	Caustic feeder
2	Recycle caustic effluent storage tank
4	Recycle caustic solution pump
9	Reactor slurry feed pump
9	Reactor vessel with agitators and drives

Table C.5 (continued)

Quantity	Description
4	Slurry cooler
16	Clean coal filter with all auxiliaries
4	Clean coal collection conveyor
2	Clean coal transfer conveyor
8	Distributing conveyor
16	Clean wet coal surge bin
32	Vibrating feeder
32	Coal dryer
4	Clean dry coal collection conveyor
2	Clean dry coal transfer conveyor
1	Clean dry coal distributing conveyor
2	Filtrate storage tank
4	Regenerator feed pump
2 2	Regeneration tower
2	Regenerator underflow storage tank
6	Slurry feed pump
3	Filter with auxiliaries
2	Effluent-sodium carbonate reactor vessel with agitators and drive
4	Lime feeder
4	$CaCO_3$ slurry pump
3	Filters - $CaCO_3$ - with auxiliaries
2	Wet $CaCO_3$ collection conveyor
5	Bucket elevator
6	Distributing conveyor
23	Lime kiln with feeder, cooler, collecting conveyor
1	Lime transfer conveyor
1	Lime storage bin
4	Lime feeder
1	Precipitated solids filter cake collection conveyor

Table C.5 (continued)

Quantity	Description
1	Precipitated solids filter cake transfer conveyor
2	H_2S surge tank
2	H_2S compressor
	Sulfur recovery unit; tail-gas cleanup; sulfur storage and loadout
1	15,000-ton dry coal silo with piling
2	Automatic coal sampling units
24	Vibrating feeder
1	Prepared coal loadout conveyor
1	Belt scales
1	Loadout bin, tower, controls, and auxiliaries
1	Automatic undertrack scales
	Process steam and power generation plant
	Water supply and complete treatment system

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

7. REFERENCES

1. J. A. Cavallaro, M. T. Johnston, and A. W. Deurbrouck, Sulfur Reduction Potential of the Coals of the United States, U.S. Bureau of Mines Report of Investigations No. 8118, 1976.

2. W. A. Selvig and F. H. Gibson, Analysis of Ash from United States Coals, U.S. Bureau of Mines Bulletin No. 567, 1956.

3. Personal communication, McNally-Pittsburgh Manufacturing Corporation, Pittsburgh, Kansas.

4. P. T. Luckie and E. A. Draeger, "The Very Special Considerations Involved in Thermal Drying of Western Region Coals," Coal Age, pp. 106-9 (January 1976).

5. R. C. Ellman, L. E. Paulson, and S. A. Cooley, "Commercial Scale Drying of Low Rank Western Coals, Part I — Rail Shipment Test Observations," presented at Lignite Symposium, Grand Forks, N.D., May 14-15, 1975.

6. W. T. Abel et al., Removing Pyrite from Coal by Dry-Separation Methods, Report No. BM-R17732, U.S. Bureau of Mines, Morgantown, W. Va., 1973.

7. J. K. Kindig and R. L. Turner, Dry Chemical Process to Magnetize Pyrite and Ash for Removal from Coal, SME-AIME Preprint No. 76-F-306 for 1976 Fall SME/AIME Meeting, Denver, Colo., September 1976.

8. Personal communication with R. L. Turner, Hazen Research, Inc., Golden, Colo., Oct. 18, 1977.

9. NIOSH, Registry of Toxic Effects of Chemical Substances, 1976 edition, HEW Publication No. (NIOSH) 76-191, Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, Rockville, Md., June 1976.

10. Y. A. Liu and C. J. Lin, "Status and Problems in the Development of High Gradient Magnetic Separation (HGMS) Processes Applied to Coal Beneficiation," paper presented at the Engineering Foundation Conference on Clean Combustion of Coal, Rindge, N.H., July 31-Aug. 4, 1977.

11. D. C. Wilson, Dry Table — Pyrite Removal from Coal, Am. Chem. Soc. Div. Fuel Chem. Prepr., 22(2): 132 (1977).

12. "Interview with Dr. V. Stephen Krajcovic-Ilok," Capital Energy Letter Exclusive, Aug. 11 and 18, 1975.

13. EPRI, "Executive Summary of the Ilok Coal Cleaning Technology," Jan. 4, 1977.

14. S. L. Soo and M. Rieber, *Final Report and Evaluation of the Ilok 4-micron Coal Grinding Process*, NTIS Report No. PB-265972, December 1976.

15. R. Stefanks, R. V. Ramani, and I. K. Chopra, *The Influence of Mining Techniques on Size Consist and Washability Characteristics of Coal*, Pennsylvania State University, Office of Coal Research Contract No. 14-01-0001-390, Aug. 1, 1973.

16. J. W. Leonard and D. R. Mitchell, *Coal Preparation*, The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1968, pp. 10-28.

17. A. W. Duerbrouck, *Washing Fine-Size Coal In a Dense-Medium Cyclone*, Report No. RI 7982, U.S. Bureau of Mines, Pittsburgh Energy Research Center, Pittsburgh, Pa., 1974.

18. *Coal Age*, p. 231 (July 1963); p. 74 (December 1961).

19. M. J. Miller, *Flotation of Pyrite from Coal: Pilot Plant Study*, U.S. Bureau of Mines Bulletin No. 7822.

20. J. M. Holmes et al., *Hydrocarbonization Process Evaluation Report, Vol. I: Conceptual Design and Cost Estimate of a Commercial-Scale Facility*, Report No. ORNL-5212, prepared for the U.S. ERDA/Fossil Energy Division of Fossil Demonstration Plants, Oak Ridge, Tenn., July 1977.

21. Fluor Utah, Inc., *Economic System Analysis of Coal Preconversion Technology, Phase I, 4, Large Scale Coal Processing for Coal Conversion*, prepared for U.S. ERDA, Contract No. E(49-18)-1520, Fluor Utah, Inc., San Mateo, Calif., July 1975 (revised May 28, 1976).

22. "Multi-Stream Coal Cleaning System," *Coal Age*, pp. 86-89 (January 1976).

23. D. V. Keller, Jr., C. D. Smith, and E. F. Burch, "Demonstration Plant Test Results of the Otisca Process Heavy Liquid Beneficiation of Coal," paper presented at the Annual SME-AIME Conference, Atlanta, Ga., Mar. 7, 1977.

24. H. H. Murray, "High Intensity Magnetic Cleaning of Bituminous Coal," paper presented at the Second Symposium on Coal Preparation, NCA/BCR Coal Conference and Expo III, Louisville, Ky., Oct. 19-21, 1976.

25. Y. A. Liu and C. J. Lin, "Assessment of Sulfur and Ash Removal from Coals by Magnetic Separation," *IEEE Trans. Magn.* MAG-12(5): 538 (1976).

26. J. A. Oberteuffer, "Engineering Development of High Gradient Magnetic Separators," *IEEE Trans. Magn.* MAG-12(5): 444 (1976).

27. C. E. Capes, A. E. Smith, and I. E. Puddington, "Economic Assessment of the Application of Oil Agglomeration to Coal Preparation," *CIM Bull.* 67: 115 (1974).

28. O. C. Ralston, *Coal Age* 22: 911 (1922).

29. A. H. Brisse and L. W. McMorris, Jr., *Mining Eng.* 10: 258 (1958).

30. *Coal Week*, Mar. 15, 1976.

31. C. E. Capes, A. E. McIlhinney, and R. D. Coleman, "Beneficiation and Balling of Coal," *Trans. Soc. Min. Eng. AIME* 247(13): 233 (1970).

32. E. P. Koutsoukos et al., *Meyers Process Development for Chemical Desulfurization of Coal*, Vol. 1, Report No. EPA-600/2-76-143a, Environmental Protection Agency, May 1976.

33. *Chem. Eng.* 84(2): 7 (1977).

34. E. P. Stambaugh et al., "Environmentally Acceptable Solid Fuels by the Battelle Hydrothermal Coal Process," presented at the Second Symposium on Coal Utilization, Louisville, Ky., Oct. 21-23, 1975.

35. W. Worthy, "Hydrothermal Process Cleans Up Coal," *Chem. Eng. News*, pp. 24-25 (July 7, 1975).

36. L. Reggel et al., "Preparation of Ash-Free, Pyrite-Free Coal by Mild Chemical Treatment," *Am. Chem. Soc. Div. Fuel Chem. Prepr.* 17(1): 44-48 (1972).

37. L. Reggel et al., "Preparation of Ash-Free, Pyrite-Free Coal by Mild Chemical Treatment," paper presented at the 164th Semiannual Meeting of the American Chemical Society, September 1972.

38. P. H. Howard and R. S. Datta, "Chemical Comminution: A Process for Liberating the Mineral Matter from Coal," *Am. Chem. Soc. Div. Fuel Chem. Prepr.* 22(2): 62 (1977).

39. P. H. Howard, A. Hanchett, and R. G. Aldrich, *Chemical Comminution for Cleaning Bituminous Coal*, Clean Fuels from Coal Symposium II Papers, Institute of Gas Technology, Chicago, Ill., June 23-27, 1975.

40. S. S. Sareen et al., *The Use of Oxygen/Water for Removal of Sulfur from Coals*, preprint *50c*, 80th AIChE National Meeting, Boston, Mass., Sept. 7-10, 1975.

41. J. C. Agarwal et al., "Chemical Desulfurization of Coal," *Min. Congr. J.* 6193): 40-43 (1975).

42. S. S. Sareen, "Sulfur Removal from Coals: Ammonia/Oxygen System," paper presented at the 173d National ACS Meeting, Division of Fuel Chemistry, New Orleans, Mar. 21-25, 1977.

43. Personal communication with L. J. Petrovic, Manager, Process Engineering and Economic Evaluation, Ledgemont Laboratory, Kennecott Copper Corp., Lexington, Mass., Mar. 22, 1977.

44. A. F. Diaz and E. D. Guth, "Coal Desulfurization Process," U.S. Patent No. 3,909,211 issued Sept. 30, 1975.

45. E. D. Guth and J. M. Robinson, *Coal Desulfurization Process*, KVB Handout No. B-3, KVB Engineering, Inc., Feb. 15, 1977.

46. S. Friedman, R. B. La Count, and R. P. Warzinski, "Oxidative Desulfurization of Coal," *Am. Chem. Soc. Div. Fuel Chem. Prepr.* 22(2): 132 (1977).

47. Personal communication with Dr. Beckberger, ARCO Research Center, Harvey, Ill., Nov. 22, 1977.

48. Personal communication with W. Slaughter, EPRI, Palo Alto, Calif., Nov. 22, 1977.

49. M. P. Silverman, M. H. Rogoff, and I. Wender, *Appl. Microbiol.* 9: 491 (1961).

50. W. W. Leather, S. A. Braley, and L. D. McIntyre, *Appl. Microbiol.* 1: 61 (1953).

51. M. P. Silverman, M. H. Rogoff, and I. Wender, "Removal of Pyritic Sulfur from Coal by Bacterial Action," *Fuel* XLII: 113 (1963).

52. R. Salmon, *PRP — A Discounted Cash Flow Program for Calculating the Production Cost (Product Price) of the Product from a Process Plant*, Report No. ORNL-5251, March 1977.

ORNL/TM-5953
Dist. Category UC-90d

INTERNAL DISTRIBUTION

1. C. R. Boston
2. J. E. Campbell
3. H. D. Cochran, Jr.
4. E. Copenhaver
5. R. M. Davis
6. M. S. Edwards
7. D. M. Eissenberg
8. J. F. Fisher
9. R. C. Forrester III
10. E. C. Fox
11. W. Fulkerson
12. E. L. Fuller
13. W. R. Gambill
14. T. M. Gilliam
15. R. W. Glass
16. H. F. Hartman
17. J. R. Hightower
18. E. C. Hise
19. R. S. Holcomb
20. J. M. Holmes
21. J. K. Huffstetler
22. A. R. Irvine
23. J. E. Jones, Jr.
24. O. L. Keller
25. K. H. Lin
26. R. E. MacPherson
27. J. P. Meyer
28. B. Niemann
29. L. C. Oakes
30. B. R. Rodgers
31. T. H. Row
32. G. Samuels
33. C. D. Scott
34. M. Siman-Tov

35-44. S. P. N. Singh

45. I. Spiewak
46. M. G. Stewart
47. R. A. Strehlow
48. O. W. Thomas, Jr.
49. W. C. Ulrich
50. D. Van Dusen
51. J. S. Watson
52. C. S. Yust
53. F. C. Zapp

54-55. Central Research Library

56. Document Reference Section
57. Laboratory Records, ORNL-RC

58-60. Laboratory Records

61. ORNL Patent Section
62. G. R. Choppin (consultant)
63. L. James Colby, Jr. (consultant)
64. E. L. Gaden, Jr. (consultant)
65. L. E. Swabb, Jr. (consultant)
66. K. D. Timmerhaus (consultant)

EXTERNAL DISTRIBUTION

Department of Energy, Fossil Energy, 20 Massachusetts Ave. N.W.,
Washington, D.C. 20545

67. E. K. Bastress

68-70. C. W. DiBella

71. C. W. Draffin
72. C. W. Knudsen
73. E. J. Lievens, Jr.
74. C. T. Miller

75. Office of Assistant Manager, Energy Research and Development,
DOE, ORO, Oak Ridge, Tenn. 37830
76. R. C. Corey, Department of Energy, Fossil Energy, 400 First Street,
Washington, D.C. 20545
77. J. Paone, Department of Energy, Fossil Energy, 4040 N. Fairfax Drive,
Arlington, Va. 22203
78. W. E. Warnke, Department of Energy, Fossil Energy, 4040 N. Fairfax Drive,
Arlington, Va. 22203
79. W. A. Schmidt, Department of Energy, 4040 N. Fairfax Drive,
Arlington, Va. 22203

80. T. J. George, Department of Energy, Process Evaluation Office, P.O. Box 880, Morgantown, W. Va. 26505
81. J. R. Duda/Library, Department of Energy, Process Evaluation Office, P.O. Box 880, Morgantown, W. Va., 26505
82. D. J. Boron, Department of Energy, Coal Preparation and Analysis Laboratory, 4800 Forbes Ave., Pittsburgh, Pa. 15213
83. A. W. Deurbrouck, Department of Energy, Coal Preparation and Analysis Laboratory, 4800 Forbes Ave., Pittsburgh, Pa. 15213
84. S. Friedman, Department of Energy, Pittsburgh Energy Technology Center, 4800 Forbes Ave., Pittsburgh, Pa. 15213
85. P. S. Jacobsen, Colorado School of Mines Research Institute, P.O. Box 112, Golden, Co. 80401
86. T. A. Sladek, Colorado School of Mines Research Institute, P.O. Box 112, Golden, Co. 80401
87. J. S. Foster, Jr., Vice President of Energy, TRW, Inc., 7600 Colshire Drive, McLean, Va. 22101
88. S. S. Sareen, Energy Systems Group of TRW, Inc., 7600 Colshire Drive, McLean, Va. 22101
89. T. D. Wheelock, Department of Chemical Engineering, Iowa State University, Ames, Iowa 50011
90. C. E. Packard, McNally-Pittsburg Manufacturing Corporation, Kansas Division, P.O. Drawer D, Pittsburg, Ks. 66762
91. Randy Cole, TVA Energy Research, 1320 Commerce Union Bank Building, Chattanooga, Tn. 37401
92. W. C. Yee, Applied Research and Education Staff, Division of Environmental Planning, TVA, 261-401 Building, Chattanooga, Tn. 37401
93. A. Sood, Research-Cottrell, P.O. Box 750, Bound Brook, N.J. 08805
94. R. Natarajan, Texas Eastern Transmission Corporation, P.O. Box 2521, Houston, Tx. 77001
95. K. K. Koh, American Natural Service Company, One Woodward Ave., Detroit, Mi. 48226
96. Y. A. Liu, Department of Chemical Engineering, Auburn University, Auburn, Al. 36830
97. J. K. Kindig, Hazen Research Inc., 4601 Indiana Street, Golden, Co. 80401
98. P. H. Howard, Syracuse Research Corporation, Merrill Lane, University Heights, Syracuse, N.Y. 13210
99. D. V. Keller, Jr., Otisca Industries Limited, P.O. Box 211, Lafayette, N.Y. 13084
100. P. J. Phillips, Gibbs & Hill, Inc., 393 Seventh Ave., New York, N.Y. 10001
101. R. B. LaCount, Waynesburg College, Waynesburg, Pa. 15370
102. L. J. Petrovic, Ledgemont Laboratory, Kennecott Copper Corporation, 128 Spring Street, Lexington, Ma. 02173
103. V. S. Krajcovic-Ilok, Ilok Powder Company, Inc., 1065 National Press Building, Washington, D.C. 20045
104. J. Jones, Institute for Mining and Minerals Research, 213 Bradley Hall, University of Kentucky, Lexington, Ky. 40508
105. P. R. Dugan, College of Biological Sciences, Department of Microbiology, Ohio State University, 484 West 12th Ave., Columbus, Oh. 43210
106. E. P. Stambaugh, Battelle Columbus Laboratories, 505 King Ave., Columbus, Oh. 43201

107. S. L. Goren, National Science Foundation, Engineering Division, Washington, D.C. 20550
108. K. A. Rogers, Engineering Societies Commission on Energy, Inc., 444 N. Capital N.E., Suite 405, Washington, D.C. 20015
109. R. A. Meyers, Defense and Space Systems Group of TRW, Inc., One Space Park, Redondo Beach, Ca. 90278
110. D. C. Wilson, Central Engineering Laboratories, FMC Corporation, 1185 Coleman Ave., Santa Clara, Ca. 95052
111. E. D. Guth, KVB, Inc., 17332 Irvine Blvd., Tustin, Ca. 92680
112. A. Murphy, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, Ca. 91103
113. W. W. Slaughter, Electric Power Research Institute, 3412 Hillview Drive, P.O. Box 10412, Palo Alto, Ca. 94303
114. K. Clifford, Electric Power Research Institute, 3412 Hillview Drive, P.O. Box 10412, Palo Alto, Ca. 94303
115. M. A. Ghaly, Bechtel Corporation Research and Engineering, P.O. Box 3965 (50/16/A26), San Francisco, Ca. 94119
116. C. E. Capes, Division of Chemistry, National Research Council Canada, Ottawa, Canada K1A OR6
117. A. Baker, Economic Assessment Service, NCB (IEA Services) Ltd., 15/15 Lower Grosvenor Place, London SW1W OEX, England
118. S. Ergun, Lawrence Berkeley Laboratory, Berkeley, Ca. 94720
119. D. R. Alison, Arthur D. Little, Inc., Acorn Park, Cambridge, Ma. 02140
120. W. McCarthy, Environmental Protection Agency, 401 M Street, S.W., Room 631, Washington, D.C. 20460
121. J. D. Kilgroe, Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27771
122. W. J. Rhodes, Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27771
123. J. Gray, Department of Energy, Pittsburgh Energy Technology Center, 4800 Forbes Ave., Pittsburgh, Pa. 15213

124-432. Given distribution as shown in TID-4500 under Coal Conversion and Utilization--Liquefaction category.

☆U.S. GOVERNMENT PRINTING OFFICE: 1979-748-189/441