Benefit-Cost Analysis of Selected DOE/OHER Investments in Coal Liquefaction

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SUMMARY

The work described in this document is based on studies conducted by the Pacific Northwest Laboratory (PNL) for the Office of Health and Environmental Research (OHER), U.S. Department of Energy (DOE). The objective of this effort was to perform a benefit-cost analysis on selected OHER research investments in coal liquefaction. Specifically, the analysis focused on the costs of, and benefits which can be realized from, research showing that mutagenic and carcinogenic activity resides in coal liquids boiling above 650 to 750°F, and that biological activity can be substantially reduced through hydrotreatment of these materials. We contend that OHER-funded investigations will enable industry to meet anticipated health and safety standards and also realize future capital and operating cost savings through a number of possible process modifications. One option is to hydrotreat part, rather than the whole high-boiling-range liquid product.

BACKGROUND

Various health problems, ranging from "black lung" disease to scrotal cancer, have long been associated with the mining and use of coal. Epidemiologic studies of workers in coking and coal gas plants in the United States, Great Britain, and Japan show there is a relationship between the incidence of lung cancer and the extent of exposure in the workplace. Furthermore, in the early 1950s, at a small plant operated by the Union Carbide Corporation in Institute, WV, it was shown that skin cancer might be increased where pyrolysis was used to convert coal to a liquid product.

Following the Arab oil embargo of 1972 to 1973, there was renewed interest in the United States in producing liquids from coal. However, the health risks associated with coal liquefaction were not well understood. Concern for potential health and environmental risks that might be present led developers to consider precautionary measures in the design and operation of early coal liquefaction pilot plants. For example, great care was taken to minimize exposure of workers to process streams. Precautions included daily changes of clothing and bathing, personnel monitoring for contamination, and workplace monitoring for the presence of potentially noxious agents. Furthermore, medical surveillance was established to monitor potential changes in the health of workers in these pilot plants. Certain populations were excluded from work areas. Some process developers did not allow women of childbearing age to work in areas where they might be exposed to noxious chemicals because of the potential for occurrence of fetal abnormalities.

These same concerns also stimulated interest in plant designs that would reduce exposure of workers to process streams and fugitive emissions in pilot plants and future commercial facilities. During the early 1970s, several alternatives were discussed. Based on petroleum industry experience, one potential option was to add hydrogen to the coal-derived liquid in amounts sufficient to break down aromatic-ring structures. Hydrogenation, using a catalytic system, could be performed on a broad boiling-range of distillates. The process associated with this type of practice is commonly referred to as hydro-treatment. This was the situation that prevailed before OHER began funding research on the toxicological effects of coal-derived liquids.

IMPACT OF DOE RESEARCH

Based in large part on the lack of specific information about the nature and magnitude of health impacts that could occur from commercialization of a coal liquefaction industry, DOE initiated a broad-based program to study the potential health and environmental fate and effects of process streams from several coal liquefaction process options. Responsibility for this research was assigned to OHER. While it is not possible to adequately characterize all the important results of this research program in the space and time available, specific results that are important for the purpose of this analysis include findings that:

- the toxicity and teratogenic potential of coal liquids boiling below 450°F is small,
- mutagenic and carcinogenic activity is typically expressed in coal liquids boiling above 750°F,
- mutagenic and carcinogenic activity increases markedly in coal liquids boiling above 800°F.

Additional research is currently underway to evaluate the relationship between the incidence of fetal abnormalities and exposure to materials boiling from 450 to 900°F.

Based on the above findings, OHER funded research to evaluate the effect of various hydrotreatment levels on the biological activity of coal-derived liquids. Studies using the Ames assay or mammalian cell transformation assays indicated that hydrotreatment was effective in reducing biological activity of coal-derived liquids. Skin-painting studies demonstrated that carcinogenicity was also reduced by hydrotreatment. Studies in progress are evaluating the effects of hydrotreatment severity on biological activity. However, it ap-

pears reasonably clear that health risks can be reduced by hydrotreating materials that boil above 750°F. Materials boiling below 750°F could be marketed directly without significant risk to individuals exposed to these products.

BENEFIT-COST FRAMEWORK

The benefit-cost analysis presented in this report is based on the premise that, in the absence of OHER research, developers of commercial coal-liquefaction processes would (at some time) have had to generate chemical, health and environmental data for new coal-liquefaction products in accordance with the Toxic Substances Control Act. This effort would have revealed that heavy distillate (i.e., the cut with a nominal boiling range from 600 to 900°F) possesses high biological activity relative to other coal-liquefaction products and analogous petroleum-derived materials. Consequently, some level of treatment or control would be required to minimize the potential environmental and health risk of using this material commercially.

There are substantial differences between the capital and operating costs associated with hydrotreating the full boiling range of materials, as opposed to those that boil at temperatures greater than 750°F. The cost differential between full and partial hydrotreatment, once incorporated in a development scenario for the direct coal liquids industry, provides the basis used in this study for approximating the potential benefits associated with relevant OHER research investments. Properly discounted to the present, the present value of these cost savings, less the cost of relevant OHER research projects, represents a lower-bound estimate of the net benefits attributable to the initial investment made by the public sector.

OHER RESEARCH COST ESTIMATES

OHER investments in coal liquefaction research are shown in Table 1. Between 1975 and 1981, OHER invested about 100.4 million dollars in coal-liquefaction research. Of this total, 79.2 million dollars were allocated to the Health Effects Research Division and the Physical and Technological Research Division, which together were responsible for funding the studies on which our benefit estimates are based. While not all projects funded by these divisions were directly related to those benefits, more detailed cost breakdowns were not possible.

TABLE 1. OHER Funding in Coal Liquefaction Research, 1975-1982 (Millions of Current Dollars)¹

Year	Health- and Technology- Related Research	Other Research	Total Funding
1982	15.0	3.6	18.6
1981	14.8	3.1	17.9
1980	13.3	2.6	15.9
1979	12.2	2.0	14.2
1978	9.2	3.5	12.7
1977	7.4	3.7	11.1
1976	4.2	1.7	5.9
1975	<u>3.1</u>	<u>1.0</u>	<u>4.1</u>
TOTALS:	79.2	21.2	100.4

¹Source: Office of Health and Environmental Research (DOE)

All estimates in Table 1 are in current dollars. Since all cost-saving estimates used in this study are in constant 1982 dollars, we adjusted the

79.2 million dollar figure for inflation. During this period, the index of nondefense Federal government purchases of goods and services rose at an annual average rate of about 9%. Using this rate to inflate pre-1982 research expenditures, the constant 1982 dollar OHER investment in health and technology-related research is calculated to be about 101 million dollars.

CAPITAL AND OPERATING COST SAVINGS ESTIMATES

The capital and operating cost savings associated with partial, as opposed to full hydrotreatment, are shown for the SRC-II process in Table 2. The basis for estimating hydrotreating costs was a recent study by Chevron Research Company. All estimates are based on a 50,000 barrels/calendar day (B/CD) standard plant. High, medium and low capital cost savings estimates are shown in Table 2 to account for the uncertainty in the estimates. The estimated capital cost savings range from 98 to 174 million 1982 dollars. The annual operating cost savings are estimated to be about 7 million 1982 dollars.

TABLE 2. Heavy Distillate Hydrotreating Cost Savings for SRC-II Coal Liquefaction

Cost Element	Cost Savings, \$MM (1982) ¹		
	High	Medium	Low
Capital	174.42	142.50	98.04
Annual Operating	6.95	6.95	6.95

¹Difference in cost between hydrotreating all heavy distillate versus treating only that boiling above 750°F

PROJECTED DEVELOPMENT OF THE DIRECT COAL LIQUIDS INDUSTRY

The development scenarios used to determine the temporal sequence of potential capital and operating cost savings resulting from OHER-funded research are based on the nominal production scenario developed for the Environmental Protection Agency (EPA). That scenario for direct coal liquids envisions construction of a single 50,000 B/CD plant to come on-line at full production between 1988 and 1992. After 1993, six additional plants are to be added. The last plant is projected to come on-line at full capacity in the year 2000. At that point, maximum production of 350,000 B/CD is achieved. None of the scenarios presented in the EPA report takes into account industry development after the year 2000.

The nominal production scenario contains little detail about the sequencing of plant construction and is also unrealistic. In order to achieve full production from the first plant by 1988 to 1992, construction of this plant would have to be underway at this time--which is not the case. To remedy these two problems, we modified the EPA scenario to include greater detail about plant construction and sequencing and to push the start date of this scenario ahead to a period that is more reasonable in light of current events.

The standard scenario used in this study spanned 20 years from the start of construction on the first plant to completion of construction and commencement of full capacity production for the seventh plant. The start of construction on plants two and three was lagged 3 and 6 years, respectively, behind the start of construction on the first plant to take advantage of learning by doing. Thereafter, the start of construction for the remaining plants was lagged 1 year behind the start of the previous plant.

For each plant, capital and operating costs were allocated as follows. The capital cost saving was assumed to take place 3 years after the start of construction. Operating cost savings were allocated according to a 4-year, phased start-up schedule at 46% of the cost savings 7 years after the construction start date, 74% in the next year, 96% a year later, and 100% from the ninth year until the end of the 20-year period. Each of these capital and operating cost savings components was then discounted back to 1982 on a plant-by-plant basis, using a real discount rate.

ALLOWANCES FOR UNCERTAINTY

Calculating net benefits of selected OHER-research investments in coal liquefaction is confounded by several sources of uncertainty, including:

- the exact nature of the coal liquefaction processes that will ultimately penetrate the market,
- the estimated capital and operating cost savings,
- the projected development of the direct coal liquids industry,
- the opportunity cost of future capital to firms in the industry, and
- the future rate of inflation.

It is difficult to obtain a single estimate for net benefits attributable to OHER research that simultaneously incorporates all of these sources of uncertainty. Therefore, a range of net-benefit estimates is provided through the use of sensitivity analysis. In particular, we examined the sensitivity of net benefits to:

- changes in the starting date of the standard development scenario,
- different real discount rates, and
- high, medium and low estimates of the capital cost savings associated with the use of partial hydrotreatment.

Input values used in the sensitivity analysis for these variables are shown in Table 3.

TABLE 3. Summary of Inputs Used in the Sensitivity Analysis

Variables	
Starting dates for Scenarios I, II and III	1984, 1987, 1992
Real discount rates (%)	5, 7, 10
OHER investment ¹	101.0
Capital savings ¹	98.04, 142.50, 174.42
Annual operating cost savings ¹	6.95
¹ Millions of 1982 dollars	

RESULTS

Three different sets of benefit computations were made. The first involved calculating net present value (NPV) of OHER-research benefits. This equals the sum of the discounted (back to 1982) capital and operating cost savings for the seven plants over the relevant 20-year period, less the OHER-

research investment. Results of this analysis are shown in Table 4. Major conclusions resulting from these estimates are summarized as follows:

- The estimated NPV of selected OHER-research investments is positive in all cases; the range of estimates is from 45.39 to 759.08 million dollars.
- Delays in the development of the direct coal liquids industry will have an adverse effect on the NPV of OHER-generated benefits (i.e., at a discount rate of 5%, the medium-range NPV estimate for SRC-II in Scenario I is 627.30 million dollars, whereas for Scenario III, the comparable estimate is only 391.94 million dollars.
- Increases in the discount rate intensify the adverse effect of delays in industry development (i.e., at a discount rate of 5%, the ratio of the medium-range NPV estimate for SRC-II in Scenario III to the comparable estimate for Scenario I is about 0.62, whereas the ratio of these estimates at a discount rate of 10% falls to about 0.30.

TABLE 4. Estimates of Net Present Value (NPV) for Selected¹ OHER Investment in Coal Liquefaction for Three Coal Liquids Development Scenarios Using the SRC-II Process and Real Discount Rates of 5, 7 and 10%

S ²	NPV in Millions of 1982 Dollars								
	5%			7%			10%		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
I	759.08	627.30	446.09	590.10	481.96	333.27	406.51	324.94	212.79
II	641.97	528.13	371.60	463.14	374.87	253.49	280.30	219.02	134.76
III	481.14	391.94	269.29	301.22	238.29	151.75	135.76	97.71	45.39

¹Investment costs include OHER expenditures on health effects and physical and technological research related to coal liquefaction.

²Scenario

The second calculation determined the internal rate of return (IRR). The IRR is the interest rate (or discount rate) that equates the present value of

the capital and operating cost savings with relevant OHER-research costs. As such, the IRR of an investment represents an average rate of return that can be used to show how well an investment is performing relative to other opportunities in the market.

Results of IRR calculations are summarized in Table 5. Note that, even with fairly conservative assumptions about future industry development (Scenario III) and industry cost savings (low estimate), the IRR for SRC-II is about 12%. In contrast, the current real rate of return on long-term securities in the private sector in July of 1982 was about 7 to 9%¹. This indicates that investments by the public sector in research related to the health effects of alternative coal liquefaction processes are highly competitive with comparable, private market opportunities.

TABLE 5. Internal Rates of Return (IRR) on Selected¹ OHER Investments in Coal Liquefaction for Three Coal Liquids Development Scenarios Using the SRC-II Process

Scenario	IRR (%)		
	High	Medium	Low
I	30	27	23
II	22	20	17
III	15	14	12

¹Investment costs include OHER expenditures on health effects and physical and technological research related to coal liquefaction.

¹This assumes a nominal rate of return on long-term corporate funds of about 14 to 15% and an expected rate of inflation between 6 and 7%.

The third benefit calculation involved determining the impact of selected OHER-funded investments on the cost of liquid coal products. Assuming that the full value of capital and operating cost savings was passed on to purchasers, which is unlikely, the estimated savings/barrel of product is from \$0.42 to \$1.14. While these figures appear small, it is important to realize that a hydrotreatment facility of any kind represents a relatively small proportion of the total capital cost of a coal liquefaction facility. Also, the fact that the cost savings/barrel of product are small should not detract from the NPV and IRR calculations which suggest, on the whole, that OHER's investment in coal liquefaction research represents an efficient use of public funds.

This work should be considered as a generic example of benefits that have occurred and can from timely OHER-initiated studies on new energy technologies. Although public- and private-sector interest in synthetic fuel development has lessened in the past 2 years because of decreased demand and increased availability of petroleum and natural gas, this analysis illustrates the potential benefits that can accrue when environmental research is coupled with energy technology development. Also, the public perception that energy technologies can be developed to minimize health and environmental risks may be as important as the economic benefits that accrue from this type of research.

1.0 INTRODUCTION

Between 1975 and 1982, the Office of Health and Environmental Research (OHER), U.S. Department of Energy (DOE), spent approximately 100.4 million dollars on a variety of research projects broadly related to the health and environmental fate and effects associated with coal liquefaction processes. How well was society served by these investments? Did this OHER-funded research represent an efficient allocation of resources, such that it can be said that society, as a whole, was materially better off as a result of the information produced by these investigations or did these expenditures represent a nonproductive drain on our national resources?

The original intent of this report was to seek answers to these questions by applying standard benefit-cost procedures to the full range of research projects funded by OHER during this 8-year period. However, it soon became apparent that because of: 1) the diversity of research funded by OHER in areas where benefits have traditionally been difficult (but not impossible) to quantify; and 2) the fact that the value of many benefits produced by this research are contingent upon health and environmental standards that will be set for a commercial industry that does not yet exist, such an undertaking lies well outside the bounds of time and resource constraints imposed on this project. Therefore, an effort was made to narrow the focus of the benefit-cost analysis to a specific body of research, where the impact on the industry could be identified in fairly specific and measurable terms.

In reviewing OHER research accomplishments in coal liquefaction (Gray and Cowser, 1982) and from conversations with individual researchers, it became clear that a major impact of OHER research was to demonstrate that biological activity of coal-derived liquids can be isolated in a fraction of the whole

liquid product, and that biological activity can be reduced using several process modifications. These, and other related discoveries, are of potential value to society because less costly technologies can be utilized to control the toxic side effects of coal liquefaction process materials, while still meeting health standards anticipated for the direct coal liquids industry. Economic benefits of this research were approximated in terms of the capital and operating cost differential associated with applying a particular control (hydrotreatment) to varying portions of the liquid product.

The remainder of this report consists of eight sections. Section 2.0 provides a brief overview of coal liquefaction processing. Section 3.0 sets the stage for the formal benefit-cost analysis and describes, in qualitative terms, how OHER research has increased knowledge concerning the health effects of coal liquefaction processes. This information has the potential to be used to reduce the capital and operating costs of coal liquefaction facilities.

Sections 4.0 and 5.0 detail the basic economic principles underlying benefit-cost analysis. Section 4.0 shows that the differential cost between the two treatment options represents a lower-bound estimate of the benefits of relevant OHER-funded research. Section 5.0 shows why and how future benefits must be discounted to the present to take into account the welfare costs associated with the passage of time.

The last four sections are the quantitative portions of the report. Section 6.0 provides the estimates used in the benefit-cost analysis for relevant OHER research investments and the per-plant capital and annual operating cost savings made possible by OHER research. Section 7.0 outlines the scenarios for development of a commercial direct coal liquids industry that were used to convert the per-plant capital and annual operating cost savings into year-by-year benefit estimates. Section 8.0 shows the computations used to obtain the

estimated net benefits of selected OHER research investments. Section 9.0 presents the quantitative results of these computations.

2.0 COAL LIQUEFACTION PROCESS OVERVIEW

Direct coal liquefaction involves reacting coal with hydrogen, at elevated temperature and pressure, to produce (primarily) liquid products. Coal liquefaction processes fall into three main categories:

- 1) pyrolysis: gas-solid reaction of coal in the absence of oxygen at high temperature and moderate pressure,
- 2) solvent extraction: liquid-phase reaction of coal and hydrogen in a coal-derived solvent at moderate temperature and high pressure, and
- 3) catalytic liquefaction: liquid-phase reaction of coal, hydrogen and coal-derived solvent, at moderate temperature and high pressure, in the presence of a catalyst.

Major potential products of coal liquefaction include fuel oils (e.g., middle and heavy distillates) medium- to high-BTU gas, propane and butanes, gasoline blending stocks, (e.g., naphtha) and high-boiling residuum. Byproducts, recovered from various gaseous and liquid streams, may include ammonia, elemental sulfur, tar acids (i.e., phenolic compounds), etc.

The major characteristic that distinguishes among various coal liquefaction processes is the reaction step. Pulverized coal and recycled, process-derived solvent are mixed, combined with hydrogen-rich gas, and reacted at

temperatures between 800 and 900°F and pressures from about 2000 to 3000 psi. Under these conditions, coal is dissolved in recycled solvent and converted to various hydrocarbon products. In some cases, a catalytic agent facilitates the coal liquefaction and solvent hydrogenation reactions, and alters the yields of specific products. Gaseous, liquid hydrocarbon, aqueous and solid/hydrocarbon slurry phases are separated prior to further downstream processing.

Numerous auxiliary processing steps are required in the operation of a commercial-scale coal liquefaction facility. Some of these (including fractionation, gasification, and hydrotreating) are particularly important in view of OHER-funded research results. Fractionation physically separates materials based on differences in compound boiling points. Products of the coal liquefaction process are distilled at atmospheric pressure and/or under vacuum into products/byproducts with various boiling-point ranges. Hydrogen for the coal liquefaction reaction is typically supplied by gasifying the solid, ash-bearing residuum, one of the primary byproducts of the process. This carbon-bearing material is reacted with steam and oxygen at high temperature, and at pressures varying from atmospheric to highly elevated. Composition of the resulting process stream is subsequently altered to provide the necessary hydrogen-rich gas.

Coal liquefaction products can be further processed via conventional petroleum refining methods such as hydrotreating, catalytic reforming and hydrocracking. In hydrotreating, the liquid product is reacted with hydrogen over a catalyst at moderate temperatures and high pressures, to produce various products or to meet product specifications (e.g., reduction of nitrogen, sulfur, and/or oxygen content). Naphtha (i.e., pentanes through about 350°F)

is normally the only direct coal liquefaction product for which petroleum processing is routinely specified (e.g., hydrotreating and reforming).

Although there are similarities among many direct coal liquefaction processes, there are also distinct differences in processing characteristics and product slates. The four most advanced direct liquefaction processes in the United States include Solvent Refined Coal (SRC) I and II, H-Coal, and Exxon Donor Solvent (EDS). The SRC-I and SRC-II processes are solvent extraction processes which generally produce a solid boiler fuel and distillate fuel oils, respectively. In the SRC-II process, a portion of the unreacted, coal-derived ash is recycled into the reactor to achieve a pseudocatalytic effect, thus producing lighter products than in the SRC-I process. The H-Coal process utilizes a catalyst in an ebullating bed reactor and can be operated to produce either a heavy boiler fuel or a lighter syncrude product. The EDS process is a solvent extraction system in which the recycle solvent is hydrotreated to impart "hydrogen-donor" properties, thus facilitating the liquid-phase liquefaction reactions. All processes described above have been operated at the pilot-plant scale, with coal processing capacities ranging from 6 and 50 ton/day for SRC-I, 25 ton/day for SRC-II, to ~250 ton/day each for H-Coal and EDS. Detailed conceptual designs for either demonstration- or commercial-scale facilities have been published for SRC-I, SRC-II and H-coal.

3.0 THE ROLE OF OHER RESEARCH IN COAL LIQUEFACTION HEALTH EFFECTS

This section has three primary objectives: 1) to provide a brief description of events leading to OHER investigations into health effects of various coal liquefaction processes; 2) to describe qualitatively, the impact of

OHER-funded research on these processes; and 3) to outline the assumptions on which the formal benefit-cost analysis of selected OHER investments is based.

3.1 Background

Health concerns have been associated with the use of coal for many years. Potential problems vary from the "black lung" of coal miners to the scrotal cancer noted by Percival Pott in 1775 among chimney sweeps. Epidemiologic studies of workers in coking and coal gas plants in the United States, Great Britain, and Japan showed an increased incidence of lung cancer related to the extent of exposure in the workplace. In the early 1950s, at a small plant operated by the Union Carbide Corporation in Institute, WV, it was shown that incidence of skin cancer might be increased where pyrolysis was used to convert coal to a liquid product.

In the early 1970s, interest in producing liquids from coal was renewed as United States dependency on foreign oil became more obvious. However, the possible deleterious effects of coal-derived products were known to industry and government agencies interested in developing coal liquefaction processes. Concern for the environment, coupled with the view that workers might be exposed to unacceptably high health risks, led developers to consider precautionary measures in designing and operating coal liquefaction facilities. For example, care was taken to minimize exposure of workers to process streams. Precautions included daily changes of clothing and bathing, personnel monitoring for contamination, and workplace monitoring for the presence of potentially noxious agents. Furthermore, medical surveillance programs were established to monitor potential changes in the health of workers in these pilot plants. Certain populations were excluded from work areas. For example, some

process developers did not allow women of childbearing age to work in areas where they might be exposed to noxious chemicals because of the potential for occurrence of fetal abnormalities.

Concern by industry and/or government regulatory agencies led to plant designs that would reduce worker exposure to process streams and fugitive emissions. In particular, data from Weil and Condra (1960), indicating that carcinogenicity was greater for higher-boiling materials, resulted in concern over higher-boiling distillate materials from coal liquefaction processes. Several possible mitigating actions were discussed in the literature of the early 1970s. Based on experience in the petroleum industry, one potential option was to add hydrogen to coal liquids in amounts sufficient to break down aromatic-ring structures. Hydrogenation, using a catalytic system, could be performed on a broad boiling-range of distillates. The process associated with this type of practice is commonly referred to as hydrotreatment. This was the situation that prevailed before OHER began funding research on the toxicological effects of coal-derived liquids.

3.2 Impact of OHER Research

Beginning in 1975, DOE/OHER initiated a broad-based research program to evaluate the potential health and environmental fate and effects of process materials from several coal liquefaction processes (Gray and Cowser, 1982). Substantial effort was invested to develop simple systems (microbial mutagenesis and mammalian cell cultures) to screen for possible biological activity in coal-derived materials. Other studies evaluated oral toxicity and teratologic potential of these materials. Initial data demonstrated that products boiling below about 450°F were minimally active. This was particularly true using mi-

crobial mutagenesis and mammalian cell transformation assays. Furthermore, teratologic and carcinogenic effects (as measured by skin-painting experiments) occurred with materials boiling above 450°F.

The above observations led to efforts to determine if biological activity could be further segregated into higher-boiling-range materials or into specific boiling-point cuts by additional distillation of process streams. These studies showed that mutagenic and carcinogenic activity occurred in cuts generally boiling above 650 to 700°F. Moreover, activity increased markedly in cuts boiling over 800°F. Segregation of biological activity into higher-boiling-range materials suggested that certain mitigating procedures might now be applied to a more limited set of materials than had been previously thought possible. For example, for an SRC-II fuel oil blend (boiling range of 350 to 900°F), material boiling above 700°F represented only 25% of the total mass of the blend; this percentage decreased to less than 10% when material boiling above 800°F was considered. Thus, rather than having to deal with the bulk of the material, which boils below 700 to 800°F, it is now possible to consider only the heaviest 10 to 20% for some type of treatment or control to minimize health effects.

OHER-funded research also evaluated the effects of hydrotreatment on the biological activity of coal-derived liquids. Studies of raw and hydrotreated distillates using the Ames or mammalian cell transformation assays indicated that hydrotreatment reduced the biological activity of coal-derived liquids. Skin-painting studies showed that carcinogenicity was also reduced by hydrotreatment. Studies are still in progress to evaluate the effects of hydrotreatment severity on biological activity.

Studies to identify components specifically active as skin carcinogens, suggest that polyaromatic amines and polynuclear aromatic compounds (in par-

ticular, those containing four or more aromatic rings with boiling points of 750°F or greater) are of major concern. Although the data are not complete, they now provide a basis for monitoring the workplace for materials of carcinogenic concern. This has permitted development of more reliable criteria for preventing exposure of personnel to potentially carcinogenic materials.

As stated above, coal liquids boiling above 450°F are teratogenic. Studies are now in progress to determine the relationship between occurrence of fetal effects and boiling points between 450 and 900°F. For our benefit-cost analysis, we assumed (perhaps incorrectly at this time) that compounds causing fetal effects have boiling points similar to those causing mutagenic and carcinogenic effects.

Marketing strategies for coal-derived materials have also been affected by OHER-funded research. Several potential product slates have been considered over the past several years. Initially, the slate favored marketing the high-boiling materials (those boiling from 350 to 850°F) as boiler fuels. However, information developed under OHER programs has resulted in a reconsideration of the marketability of high-boiling materials. One potential new strategy would be to market materials boiling below 750°F without further treatment. Materials boiling above 750°F would be used in-plant, gasified or hydrotreated.

3.3 Benefit-Cost Framework

Our benefit-cost analysis is based on the premise that, in the absence of OHER-funded research, developers of commercial coal-liquefaction processes would (at some time) have to generate chemical, biomedical and environmental data for new coal-liquefaction products in accordance with the Toxic

Substances Control Act. This effort would have revealed that heavy distillate (i.e., the cut with nominal boiling-range from about 600 to 900°F) possesses an inordinately high level of biological activity relative to other coal-liquefaction products and analogous petroleum-derived materials. Consequently, it is likely that some level of treatment or control would be required to minimize potential environmental and health risks of using this material commercially.

Two significant results from OHER-funded research substantially affect this situation:

1. Mutagenic and carcinogenic activity of heavy distillate occurs, primarily, in material boiling above 750°F and is associated with primary aromatic amines and polynuclear aromatic compounds.
2. Processing coal-derived distillates by conventional hydrotreating at moderate severity (i.e., hydrogen consumption ranging from 1000 to 2000 standard cubic feet [SCF] per barrel) reduces the biological activity of high-boiling materials. This may be due to deamination of aromatic amines, ring hydrogenation of all aromatics and/or decomposition of large ring structure compounds to small ring structure materials.

Thus, only material boiling above 750°F needs to be treated in some manner. Depending on the process and amount of material produced, several process modifications could be implemented to reduce the biological activity of material boiling above 750°F. Options include hydrotreating, recycling to extinction, gasification (with the residuum that boils from 900 to over 1000°F), and com-

binations of these measures. A complete design study would be required to evaluate these options and identify the most cost-effective measure(s) for reducing potential environmental and health risks. Consequently, our analysis focuses on only one option: the incremental cost of hydrotreating all of the heavy distillate versus only the material boiling above 750°F.

There are substantial differences between the capital and operating costs of hydrotreating all versus part of the heavy distillate. The estimated magnitude of this difference will be discussed in detail in Section 7.0. The cost differential between the two treatment options, once it has been incorporated into the cost of construction and operation of facilities in a commercial, direct coal liquids industry, provides the basis for approximating the potential benefits associated with selected OHER-funded research investigations. However, the investigations that produced this information required a commitment of resources on the part of DOE. Therefore, to arrive at an estimate of the net benefits that may be attributed to OHER research, the relevant research costs must be subtracted from the measure of total benefits. The result is a lower-bound approximation of net benefits associated with OHER research, consistent with the validity of the estimated cost savings and commercial development scenarios constructed for the analysis.

4.0 ECONOMIC FRAMEWORK

We contend that OHER-funded investigations into the health effects related to various coal liquefaction processes will make it possible for industry to realize future cost savings through the use of partial, rather than full, hydrotreatment to meet anticipated health and safety standards. We will

now show that this potential cost savings represents a lower bound on the value of the societal benefits that can result from this research investment.

The relationship between potential cost savings and net societal benefits generated by OHER-funded research relative to health effects of various coal liquefaction processes is shown in Figure 1. The demand curve (DD') shows the quantity of aggregate coal liquids (Q) that purchasers choose to take from the market, per unit time, for each aggregate product price (P). The industry supply curve, assuming full hydrotreatment, is shown by the line OS_0 . This curve indicates the output, per unit time, that producers in the industry are willing to supply at each product price. The industry supply curve is sometimes called the marginal cost curve because each point on the curve OS_0 represents the marginal cost measured along the vertical axis that is consistent with the corresponding output on the horizontal axis. Market equilibrium occurs at the point of intersection between the industry supply and demand curves (e.g., M_0), where Q_0 units of aggregate output are supplied in the market at price P_0 , which also corresponds to the marginal production cost, MC_0 .

The economic benefits associated with this market equilibrium are represented by the area ODM_0 . Benefits to purchasers and producers of coal liquids can be broken down as follows. Purchasers would be willing to pay as much as D dollars for the product. In fact, the actual purchase price is only P_0 dollars. Thus, the most amount of money that purchasers would be willing to pay for Q_0 is shown by the area under the demand curve and to the left of the line M_0Q_0 , or ODM_0Q_0 . However, in order to obtain Q_0 units of the product, purchasers must pay the market price, P_0 . Thus, the benefits experienced by purchasers as a result of being able to purchase Q_0 units of output at the lower price is equal to their total willingness to pay for Q_0 , less the amount of

FIGURE 1. Conceptual Analysis of Benefits from OHER Investment in Coal Liquefaction

their expenditure, $P_0 \times Q_0$. This leaves the triangular area P_0DM_0 as a measure of the net benefits experienced by purchasers.

The benefit to producers associated with the market equilibrium P_0, Q_0 is the difference between revenues they receive from the sale of product, less the capital and operating costs associated with this level of production. Revenues received by producers are identical to the expenditures of purchasers and are measured by the rectangular area $OP_0M_0Q_0$, i.e., $P_0 \times Q_0$. The cost of producing Q_0 units of output, assuming all costs are variable, is equal to the area under the marginal cost curve OS_0 , or OM_0Q_0 . The difference between these two areas, which is represented by the area OP_0M_0 , indicates the net benefit to producers associated with the market equilibrium P_0, Q_0 .

Information produced by OHER-funded research will enable firms in the coal liquids industry to reduce the capital and operating costs of coal-liquefaction facilities, while maintaining health standards that are still consistent with full hydrotreatment. This will reduce the marginal costs of production in the industry over a wide range of output, as shown in Figure 1 by a new-industry supply curve, OS_1 , which lies to the right of the original marginal cost curve, OS_0 . Given that firms in the industry can produce the same level of output using partial hydrotreatment at a lower marginal cost than would have been possible using full hydrotreatment, a new market equilibrium is established at M_1 where point Q_1 units of the product are supplied in the market at a price P_1 .

Note that the net benefits to purchasers have increased from P_0DM_0 to P_1DM_1 , while net producer benefits have fallen slightly from OP_0M_0 to OP_1M_1 . In general, technological innovations characterized by a shift to the right in the supply curve of an industry always lead to a net increase in the benefits experienced by purchasers. However, the direction of the change in net pro-

ducer benefits depends, in a more complex fashion, on the magnitude of the shift in the supply curve and the curvature properties of the demand and supply curves at M_0 and M_1 . Thus, a decline in producer profits is generally not an inevitable result of technological innovation, nor of the information produced by OHER-funded research. Nonetheless, some redistribution of the share of net benefits between purchasers and producers is usually implied by technological innovations that have the effect of shifting the supply curve of an industry to the right, as shown in Figure 1.

More important for the moment than the redistributive effects of technological innovations is the change in the combined value of the economic benefits experienced by purchasers and producers. In Figure 1, the result of the shift in the industry supply curve has been to increase the value of benefits by an amount equal to the pie-shaped area, OM_0M_1 . This area represents the potential annual net benefit as a result of OHER-funded research designed to characterize the health effects of various coal liquefaction processes. However, the benefits measured in this report do not capture the full value of the benefits contained within the area OM_0M_1 . The cost savings that have been estimated here approximate the difference between the area under the original marginal cost curve (i.e., full hydrotreatment) and the area under the new marginal cost curve (i.e., partial hydrotreatment), at the old level of output. This cost savings is represented by the area OM_0A , and as such, represents a lower bound on the net benefits measured by the larger area, OM_0M_1 .

It must be made clear, at this point, that the cost savings estimated in this report are based on an approximation of the area OM_0A . Subsequent sections will describe in greater detail how both capital and operating cost savings were obtained for the direct coal liquids industry. However, the information used to construct these estimates was not based on the projected supply

and demand curves shown in Figure 1. While it is conceivable that information concerning future energy technologies, including direct coal liquefaction, could be integrated within the framework of existing large-scale models of the energy economy, such an effort is beyond the time and resource limitations imposed on this analysis. As a result, information about alternative coal liquefaction processes was combined with available information about the expected buildup of facility capacity and production in the direct coal liquids industry to produce estimates of the potential cost savings that could be ascribed to OHER-funded research. Because existing scenarios for the industry could not be adjusted by any systematic means to reflect the possible increase in industry output (i.e., from Q_0 to Q_1) associated with the results of OHER-funded research, the estimated cost savings presented in subsequent pages can be construed only as an approximation of the area OM_0A .

5.0 PRESENT-VALUE MEASURES OF BENEFITS AND COSTS

The previous section provides the theory for using the cost savings accrued in the construction and operation of coal liquefaction facilities as a lower bound on the value of the benefits created by OHER-funded research. To estimate net benefits, we must consider two additional factors:

- The periodic benefits shown in Figure 1 will change over time as the number of facilities in the industry increases,
- The costs of OHER-funded research and the benefits experienced by purchasers and producers of coal liquids do not occur in the same time periods.

Individuals, be they producers or consumers, are not indifferent to the benefits of an investment that are realized immediately and benefits that are

realized in the future. The latter benefits are less valuable because they are not available for immediate consumption and/or reinvestment. Investors usually demand a premium in lieu of foregone consumption or investment opportunities when they lend their money to other individuals or firms. This premium is reflected in interest rates. Accordingly, to allow for these welfare costs attributed to passage of time, discount rates must be used to convert benefits and costs to common, present value units. Specifically, costs and benefits incurred in future years must be multiplied by a discount factor, $(1 + r)^{-t}$, where r is the discount rate used to evaluate the investment and t is the index of the year when the cost or benefit will occur. Note that as t becomes larger, the discount factor and the present value of costs or benefits associated with that factor decline. Similarly, the larger the discount rate used in evaluating an investment, the smaller will be the present value of the costs and/or benefits occurring in any future year.

Selection of an appropriate discount rate for evaluating the costs and benefits of public investments has traditionally been a controversial topic in economics (Harberger, 1968; Baumol, 1968; Marglin, 1968). Basically, there are two schools of thought (Howe, 1971, 1979). One view is that the costs and benefits associated with public investment should be discounted at a rate that reflects the private opportunity cost of capital in those markets affected by the investment. Proponents of this view argue that resources will be used inefficiently if the discount rate used in evaluating public expenditures is less than the marginal rate of return these funds would yield if invested in the private sector of the economy. The opposing view is that the public sector has a particular responsibility to future generations and therefore should place greater value on future benefits and costs than does the opportunity cost of capital in relevant private markets. The discount rate advocated by

proponents of this position is referred to as the rate of social time preference, a rate that is thought to better reflect society's views about the optimal allocation of resources between the present and the future.

For our purposes, the choice of an appropriate discount rate is further complicated by a number of sources of uncertainty, including:

- the estimated capital and operating cost savings,
- the projected development of the direct coal liquids industry,
- opportunity cost of capital to firms in the industry in future years, and
- the impact of future inflation on the prices of coal liquefaction products and on construction and operating costs of facilities.

It may be appropriate to add a risk premium to the rate of discount that is selected initially to reflect these sources of uncertainty.

Given this brief introduction to discounting, the risk-adjusted net present value (NPV) of an investment of C dollars in the initial period that results in a stream of benefits (B_t) between year 1 and the terminal period of evaluation (N) can be expressed as:

$$NPV = \sum_{t=1}^N (1 + \hat{r} - \dot{p})^{-t} B_t - C \quad (1)$$

where $\hat{r}$ is the risk adjusted discount rate and $\dot{p}$ is the expected rate of inflation affecting the money values used to calculate B_t . The discount factor shown in Equation (1) differs slightly from the discount factor presented earlier as $(1 + r)^{-t}$. The difference, aside from the risk adjustment reflected in $\hat{r}$, is that the discount factor shown in Equation (1) is expressed in real

terms, whereas the previous discount factor was expressed in nominal terms. The use of a real discount rate requires that annual benefits, measured by B_t , and the value of the initial investment be expressed in constant dollar terms (i.e., adjusted for inflation).

Equation (1) provides the basis for calculating the net present value of benefits associated with OHER-funded research relative to health effects associated with various coal liquefaction processes. However, this formulation is extremely general. Section 6.0 is therefore devoted to obtaining estimates for the cost of relevant OHER-funded research and the capital and operating cost savings that these investigations have made possible.

6.0 ESTIMATES OF OHER RESEARCH INVESTMENTS AND RELATED COAL LIQUEFACTION COST SAVINGS

From 1975 to 1981, OHER invested about 100.4 million dollars in research broadly related to coal liquefaction. Not all of the funding provided by OHER during this period was in areas directly related to evaluating potential health effects of alternative coal liquefaction processes. Therefore, we included in the value of direct OHER research costs only those expenditures allocated to projects managed by the Health Effects Research Division and the Physical and Technological Research Division. Of the 100.4 million dollars committed by OHER to coal liquefaction research between 1975 and 1982, 79.2 million dollars (roughly, 79% of the total) were provided by these two divisions (Table 1). Not all projects funded by these two divisions were directly related to the benefits calculated in this report. However, further refinement of the OHER cost investment was not possible.

TABLE 1. OHER Funding in Coal Liquefaction Research, 1975-1982 (Millions of Current Dollars)¹

Year	Health- and Technology- Related Research	Other Research	Total Funding
1982	15.0	3.6	18.6
1981	14.8	3.1	17.9
1980	13.3	2.6	15.9
1979	12.2	2.0	14.2
1978	9.2	3.5	12.7
1977	7.4	3.7	11.1
1976	4.2	1.7	5.9
1975	<u>3.1</u>	<u>1.0</u>	<u>4.1</u>
TOTALS:	79.2	21.2	100.4

¹Source: Office of Health and Environmental Research (DOE)

All values in Table 1 are in current dollars. Because all cost-saving estimates used in this report are in constant 1982 dollars, we adjusted the 79.2 million dollar figure for inflation. During this period, the index of nondefense Federal government purchases of goods and services rose at an average annual rate of about 9%. Using this average rate to inflate pre-1982 research expenditures, the constant-dollar OHER investment in health- and technology-related research is estimated to be 101 million dollars. This value was used in all benefit-cost calculations presented in Section 9.0.

The basis for estimating hydrotreating costs was a study recently conducted by Chevron Research Company (Frumkin et al., 1981). All costs were initially calculated in 1981 dollars. These estimates were converted to 1982 dollars by inflating the 1981 figures using the average annual rate of change of the aggregate facility cost index for the period from January 1, 1981 to

March 31, 1982 (14% per annum) as published in Chemical Engineering Magazine (May 31, 1982). The paper discussed plant configurations and costs for refining, nominally, 50,000 B/CD of H-Coal syncrude derived from Illinois bituminous and Wyodak sub-bituminous coals. Various product slates were evaluated, including motor gasoline, motor gasoline plus kerosene jet fuel, and motor gasoline plus No. 2 heating oil. Grass-roots plant investment and operating costs were presented, with plant configurations and capacities for various processing options. Case 3, production of No. 2 heating oil and motor gasoline from Illinois-coal-derived syncrude, was chosen as the basis for estimating incremental hydrotreating costs for our analysis. The basic processing components in Case 3 included syncrude hydrotreating; heavy naphtha hydrotreating and catalytic reforming, generation of hydrogen from some of the syncrude using partial oxidation, and miscellaneous utility, waste-treatment, and by-product recovery facilities.

One set of capital and two sets of annual operating costs were developed in our analysis for hydrotreating the whole SRC-II heavy distillate versus the fraction of the heavy distillate boiling above 750°F. A nominal 50,000-B/CD facility was assumed. Thus, based on the existing Phase Zero design, the SRC-II process produces about 11,000 B/CD of heavy distillate (Pittsburg & Midway Coal Mining Co., 1979a). Material boiling above 750°F amounts to 2700 B/CD (Pittsburg & Midway Coal Mining Co., 1979b).

Upper and lower bounds were developed for capital and operating costs (Table 2). Costs for Chevron's grass-roots refinery were increased to account for additional hydrogen production (i.e., doubling hydrogen consumption from 880 to 1760 SCF/Barrel). The lower bound on capital cost was set by subtracting capital costs for facilities in the grass-roots refinery that were part of the basic 50,000 B/CD coal liquefaction facility. Direct capital costs were

adjusted from the nominal 50,000 B/CD facility, using a capacity ratio exponent of 0.6. Working capital was adjusted linearly by capacity ratio. Operating costs from the Chevron study were adjusted to provide an upper and lower bound as follows: 1) linearly by capacity ratio, and 2) as 8% of the adjusted total capital costs. However, only the linearly ratioed operating cost savings were used in the eventual benefit-cost computations.

TABLE 2. Heavy Distillate Hydrotreating Costs for SRC-II Coal Liqfaction

Heavy Distillate Production, B/CD		Cost Element	Hydrotreating Cost ¹ , \$MM (1982)			
Whole	750°F+		Whole Material		750°F+ Material	
			High	Low	High	Low
11000 ²	2700	Capital	245.10	168.72	102.60	70.68
		Annual operating I ³	9.23	9.23	2.28	2.28
		Annual operating II ⁴	19.61	13.45	8.21	5.70

¹Based on Frumkin et al. (1981). Costs extrapolated from Case 3, producing heating oil and motor gasoline from ~50,000 B/CD of H-Coal syncrude.

²Boiling range of 550 to 900°F; adjusted production for a nominal 50,000 B/CD facility

³Ratio linearly by facility capacity

⁴Calculated as 8% of estimated capital cost

Benefits from OHER-funded research were calculated as dollars in capital and operating costs that could be saved by hydrotreating only material boiling above 750°F rather than the entire heavy distillate. Cost savings were calculated as the difference between upper-bound estimates, lower-bound estimates, and the upper bound at the high capacity minus the lower bound at the low ca-

capacity (Table 3). Cost savings for SRC-II ranged from \$98.04 to \$174.42 million for capital costs, and from \$6.95 to \$13.91 million for annual operating costs.

TABLE 3. Heavy Distillate Hydrotreating Cost Savings for SRC-II Coal Liquefaction

Cost Element	Cost Savings, \$MM (1982) ¹		
	Δ High ²	Δ Low ³	Δ (High-Low) ⁴
Capital	142.50	98.04	174.42
Annual operating I	6.95	6.95	6.95
Annual operating II	11.40	7.75	13.91

¹Difference in cost between hydrotreating all heavy distillate versus treating only that boiling above 750°F

²Difference based on upper-bound cost estimates

³Difference based on lower-bound cost estimates

⁴Difference between upper bound for whole distillate and lower bound for material boiling above 750°F

7.0 PROJECTED DEVELOPMENT OF THE DIRECT COAL LIQUIDS INDUSTRY

The development scenarios used to determine the temporal sequence of potential capital and operating cost savings created by OHER-funded research were based on the nominal production scenario developed for the Environmental Protection Agency (EPA, 1981). The nominal production scenario for direct coal liquids envisions construction of a single 50,000 B/CD facility that comes on line at full production between 1988 and 1992. After 1993, six ad-

ditional facilities are added. The last facility is projected to come on-line capacity in the year 2000, when maximum production of 350,000 B/CD is achieved. None of the scenarios in this report consider industry development after the year 2000.

The nominal production scenario contains little detail about the sequencing of plant construction and is also unrealistic. In order to achieve full production from the first plant by 1988 to 1992, construction of this plant would have to be underway at this time--which is not the case. To remedy these inconsistencies, we modified the EPA scenario to include greater detail concerning plant construction and sequencing and to advance the start date of this scenario to a period commensurate with current events.

Sequencing of plant construction and allocation of capital and operating cost savings to distinct periods in the construction and start-up phases of each facility are shown in Figure 2. The event labeled S for Plant 1 marks the start of the seven-plant construction sequence, which extends from year 0 to year 20 (in relative time), when the last plant is completed. The start of construction on the next two facilities was lagged 3 and 6 years, respectively, from the start of construction on Plant 1. Thereafter, start of construction on the remaining four plants was lagged one year behind the start of construction on each previous plant. This sequence was chosen because it provided the most leeway for "learning by doing" on the first three plants while meeting the relative time dimensions identified in EPA's nominal production scenario.

Important milestones in the construction and start-up of each facility, used to allocate capital and operating cost savings to specific points in time, are shown for Plant 1 (ASFI, 1981a). Capital cost savings are incurred in year three after construction begins, at the point labeled HC. To simplify

FIGURE 2. Plant Construction and Operational Start-up for Modified Nominal Production Scenarios.

the analysis, we assumed that costs associated with incorporating hydrotreatment capabilities in the basic coal liquefaction facility would be incurred at this time. The milestone labeled 1 marks achievement of plant operation at an estimated 23% of calendar-day capacity. In the next 3 years, labeled as 2 through 4, production increases to 58%, 93%, and 100% (10 years after the start of construction), respectively, of the 50,000 B/CD-rated plant capacity. During this period, the comparable operating cost savings were assumed to be 46, 74, 96 and 100% of the relevant annual operating cost savings (ASFI, 1981b). Thereafter, each plant was assumed to produce 50,000 B/CD of product until year 20 of the multi-plant scenario. Operating cost savings were allocated from year 1 to year 20 based on the above scenario for each of the seven plants. Thus, the first plant was assumed to run at full capacity from years 10 to 20, while the last plant experienced only a single year of full-capacity operation. Allocation of operating cost savings was terminated at this point to maintain consistency with the EPA nominal production scenario and because sensitivity analysis revealed that, at critical (i.e., high) discount rates, the present value of operating cost savings was small.

Based on the information in Figure 2, three development scenarios were constructed. The first (Scenario I), spans the period 1984 to 2004. The year 1984 is assumed to be the earliest date at which construction of the first, commercially operated coal liquefaction facility could proceed. Given the current uncertainties concerning the synthetic fuels industry in general, two additional scenarios were constructed to reflect delays in developing a direct coal liquids industry. Scenario II assumed 1987 as the starting date for construction of the first plant and 2007 as the terminal date, when full-capacity operation would be achieved for the last plant. Scenario III contained the most conservative assumptions concerning the immediate future of the synthetic

fuels industry and advanced the starting and terminal dates to 1992 and 2012, respectively. Reference dates for all three scenarios are shown in Table 4.

TABLE 4. Development Scenarios for Direct Coal Liquefaction Industry

Scenario Number	Start Construction Plant Number 1	Full-Capacity Operation Plant Number 7
I	1984	2004
II	1987	2007
III	1992	2012

8.0 CALCULATION OF BENEFIT MEASURES

Given information (Section 6.0) regarding estimated cost savings associated with partial versus full hydrotreatment, and information about the development scenarios (Figure 2 and Table 4), the calculation of net benefits attributed to OHER-funded research is as follows. For a single plant, the present value of cost savings (PV ΔC) potentially attributable to OHER-funded research is expressed as:

$$\begin{aligned}
 PV\Delta C_i = & \Delta CC \cdot \phi^{-(S_i+3)} + 0.46 \Delta OC \cdot \phi^{-(S_i+7)} + \\
 & 0.74 \Delta OC \cdot \phi^{-(S_i+8)} + 0.96 \Delta OC \cdot \phi^{-(S_i+9)} + \\
 & \sum_{t=S_i+10}^N \Delta OC \cdot \phi^{-t}
 \end{aligned} \tag{2}$$

where

$\Delta CC =$ the capital cost savings associated with partial versus full hydrotreatment in constant 1982 dollars;

$\Delta OC =$ the operating cost savings associated with partial versus full hydrotreatment in constant 1982 dollars;

$\phi =$ the risk adjusted real discount factor equal to $1 + \hat{r} - \dot{p}$;

$S_i =$ the positive difference between the construction start-up date for plant i and the base year (1982);

$N =$ the positive difference between the start of full-capacity operation by the seventh plant and 1982.

Given the present value of the cost savings for each plant, the total present value of these benefits is:

$$PVWC = \sum_{i=1}^7 PV\Delta C_i. \quad (3)$$

The estimated net present value (NPV) of benefits attributed to OHER-funded research for a given scenario is then:

$$NPV = PV\Delta C - C_0 \quad (4)$$

where C_0 represents the relevant investment by OHER in coal liquefaction research, measured in constant 1982 dollars.

At least three characteristics of Equations (2) through (4) require further explanation: 1) all monetary values for capital and operating cost savings and the initial OHER investment are expressed in constant 1982 dollars; 2) the discount rate used to calculate future capital and operating savings is expressed in real, as opposed to nominal, terms; and 3) the capital and oper-

ating cost savings for each plant are always discounted back to the base year, 1982. Thus, the passage of time plays an important role in determining the NPV of benefits associated with OHER-funded research in coal liquefaction.

The last statement may appear unrealistic since industry is not expected to expend private resources to construct and operate coal liquefaction facilities until after 1982. Because of this, one may wonder why capital and operating cost savings are discounted back to 1982 instead of to the year in which private sources are first committed to construction of each plant. Use of a 1982 basis reflects the fact that these benefits are associated with public-sector investments in research that have already been undertaken (and adjusted for inflation to the base year), not with investment by the private sector. This is reasonable since the decision to fund additional research (beyond 1982) in coal liquefaction must consider the impact of delays in developing the industry on the expected present value of future public-sector investments. If a potential investment by the public sector does not have a positive NPV because returns will not be realized until some time in the future, then discounting back to the year in which the investment is made provides a signal to decision-makers that the investment should be delayed until more favorable investment opportunities arise.

Because of the many sources of uncertainty in this analysis, we evaluated the sensitivity of the NPV of benefits in each of three scenarios to changes in several variables shown in Equation (2). These included:

- Capital Cost Savings - High, medium, and low estimates for capital cost savings were summarized in Table 4.

- Discount Rates - Three different real discount rates were used: a 5% rate, which assumes a return to the historical (i.e., before the mid-1970s) interest rate of about 3%, a 7% rate, which assumes that the real rate of interest is slightly higher, and a 10% rate.

Besides calculating a range of NPV estimates for each scenario, we also calculated internal rate of return (IRR). The IRR (in this case a real, as opposed to nominal, rate) is a measure of the average rate of return over the life of an investment. Computationally, the IRR is the value of ϕ in Equation (2), which makes $PV\Delta C$ in Equation (4) equal to the value of the initial investment, C_0 . As such, the IRR of an investment provides additional information to decision-makers about how well an investment is performing relative to other opportunities in the market. An IRR above the relevant real market rate of return is usually a sign that additional public-sector investment is warranted, whereas an IRR below the relevant market rate may indicate over-investment.

We also calculated the projected cost savings per barrel of product (CS/bbl). These cost savings were based on the representative plant model, assumed to have a productive life of 20 years. Capital savings were distributed evenly over time, from the third year after start of construction to the end of the plant's useful life, a 27-year period. Operating cost savings were allocated evenly over time from the tenth year after the start of construction to the end of the plant's useful life, a 20-year period. The accounting date used as the basis for discounting plant capacity/output was set equal, in relative terms, to the year in which the capital cost savings was incurred. Thus, although the estimated CS/bbl do not vary with the development scenario used, they are sensitive to the estimated capital and operating cost savings and the

discount rate. The CS/bbl were not discounted back to 1982 because we wanted to show the kind of benefits that could be expected when they actually occurred, rather than in relationship to the present. Finally, we assumed that all cost savings would be passed directly to purchasers of the plant's output. While this assumption is only rarely justified, the information needed to determine the distribution of these cost savings between purchasers and producers is not available.

Based on these assumptions, CS/bbl can be expressed as:

$$CS/bbl = \Delta CC \cdot \left[\sum_{t=1}^{27} \frac{18.25 \times 10^6}{(1+r-p)^t} \right]^{-1} + \Delta OC \cdot \left[\sum_{t=7}^{27} \frac{18.25 \times 10^6}{(1+r-p)^t} \right]^{-1}$$

where 18.25×10^6 represents annual output of the representative plant at 50,000-B/CD capacity for a 365-day year.

9.0 RESULTS

Before presenting actual results of the computations for NPV and IRR, we will review the range of input values used to arrive at those results. Within each of three scenarios, the information shown in Table 5 was used to calculate high, medium, and low estimates of the NPV of OHER-funded research for a coal liquefaction industry based on the SRC-II process, by discount rate. Thus, for each scenario nine NPV estimates were computed, or a total of 27 different estimates. Calculations of IRR for each scenario were based on high, medium, and low cost savings. Thus, there are only three estimates of IRR per scenario, or a total of nine estimates for all three scenarios. Finally, the estimated CS/bbl from a representative plant were calculated using

the high, medium, and low capital cost savings and real discount rates of 5, 7 and 10%.

TABLE 5. Summary of Inputs Used to Estimate Benefits and Internal Rate of Return for OHER-Funded Research

Variables	
Development scenario (I, II and III)	1984 to 2004, 1987 to 2007, 1992 to 2012
Real discount rates (%)	5, 7, 10
OHER investment (millions of 1982 dollars)	101
Capital savings (millions of 1982 dollars)	98.04, 142.50, 174.42
Annual operating cost savings (millions of 1982 dollars)	6.95

Results of the sensitivity analysis on the NPV of OHER-funded benefits are shown in Table 6. Major conclusions are summarized as follows:

- Estimated NPV of OHER-funded research is positive in all cases; the range of estimates is from 45.39 to 759.08 million dollars.
- Delays in developing the direct coal liquids industry have an adverse effect on the NPV of OHER-funded benefits; for example, at a discount rate of 5% the medium-range NPV estimate in Scenario I is 627.30 million dollars, whereas for Scenario III the comparable estimate is only 391.94 million dollars.

TABLE 6. Estimates of Net Present Value (NPV) for Selected¹ OHER Investments in Coal Liquefaction for Three Coal Liquids Development Scenarios with Real Discount Rates of 5, 7 and 10%.

Scenario	NPV in Millions of 1982 Dollars								
	5%			7%			10%		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
I	759.08	627.30	446.09	590.10	481.96	333.27	406.51	324.94	212.79
II	641.97	528.13	371.60	463.14	374.87	253.49	280.30	219.02	134.76
III	481.14	391.94	269.29	301.22	238.29	151.75	135.76	97.71	45.39

¹Investment costs include OHER expenditures on health effects and physical and technological research relative to coal liquefaction.

- Increases in the discount rate intensify the adverse effect of delays in industry development; for example, at a discount rate of 5% the ratio of the mid-range NPV estimate in Scenario III to the comparable estimate for Scenario I is approximately 0.62, whereas the ratio of these estimates at a discount rate of 10% falls to about 0.30.

The results of the IRR calculations are summarized in Table 7. The estimates range from a high of 30% real, to a low of 12%. Toward the low end, even with fairly conservative assumptions about future industry development (Scenario III) and industry cost savings (low estimate), the IRR is still about 12%. In contrast, the current real rate of return on long-term securities in the private sector in July of 1982 was about 7 to 9%¹. This indicates that investments by the public sector in research related to the health effects of alternative coal liquefaction technologies are highly competitive with comparable, private market opportunities.

The projected CS/bbl anticipated as a result of OHER-funded research in coal liquefaction (consistent with assumptions in Section 8.0) are shown in Table 8. Estimated CS/bbl range from \$0.42 to \$1.14. While these figures are not large relative to currently projected product prices, it is noteworthy that a hydrotreatment facility probably represents no more than 5 to 10% of base plant costs and that the potential capital cost savings created by the OHER investment never represents more than about 70% of the cost of a hydrotreatment facility. Thus, we do not expect the CS/bbl to be large. However, the fact that the CS/bbl are small should not detract from the NPV and IRR

¹This assumes a nominal rate of return on long-term corporate funds of about 14 to 15% and an expected rate of inflation between 6 and 7%.

TABLE 7. Real Internal Rates of Return on Selected¹ OHER Investments in Coal Liquefaction for Three Coal Liquids Development Scenarios

Scenario	IRR (%)		
	High	Medium	Low
I	30	27	23
II	22	20	17
III	15	14	12

¹Investment costs include OHER expenditures on health effects and physical and technological research relative to coal liquefaction.

calculations, which suggest, on the whole, that OHER's investment in coal liquefaction research appears to represent an economically efficient use of public funds.

TABLE 8. Projected Cost Savings per Barrel of Product for Real Discount Rates of 5, 7 and 10%.

Scenario	Cost Savings (\$1982/bbl)								
	5%			7%			10%		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
SRC-II	0.70	0.59	0.42	0.87	0.72	0.52	1.14	0.96	0.69

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