BNL # 63463

Economic Feasibility of Biochemical Processes for the Upgrading of Crudes and the Removal of Sulfur, Nitrogen, and Trace Metals from Crude Oil--Benchmark Cost Establishment of Biochemical Processes on the Basis of Conventional Downstream Technologies

Final Report FY 95

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August 1996

Prepared for:

U.S. Department of Energy
Division of Fossil Fuels
Enhanced Oil Recovery
Bartlesville Project Office
Bartlesville, Oklahoma

Contract No.: AS-405-BPSD, U.S. DOE, Division of Fossil Fuels, Bartlesville Project Office
Contractor: Associated Universities, Brookhaven National Laboratory

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Acknowledgments

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I would also like to acknowlege the valuable advice, support, provision of samples, and guidance of Art Hartstein, FE, DOE Headquarters and Ernie Zuech, DOE Bartlesville Project Office.

Note: Courtesy of other programs, notably the Educational and Minority programs, contributions of many participants are also acknowledged. These include all the students/minorities/teachers/visiting faculty and joint programs with the Department of Chemical Engineering at Howard University.

1. Executive Summary

The Department of Energy/Fossil Energy (DOE/FE) has been supporting applied bio-technical research at Brookhaven National Laboratory (BNL) for several years, focusing on the development of biochemical processes for recovery of crudes with applications in the downstream oil processing industry. Three major promising applications have been identified. They all deal with reduction of impurities from crude oil. The three impurities are sulfur, nitrogen, and trace metals. Another potentially beneficial application of biochemical downstream processing of crude oil is the breakdown of heavy ends to lighter hydrocarbons and bioconversion of oil wastes for recycling.

The downstream biotechnological crude oil processing research performed thus far is of laboratory scale and has focused on demonstrating the technical feasibility of downstream processing with different types of biocatalysts under a variety of processing conditions. Quantitative economic analysis is the topic of the present project which investigates the economic feasibility of the various biochemical downstream processes which hold promise in upgrading of heavy crudes, such as those found in California, e.g., Monterey-type, Midway Sunset, Honda crudes, and others.

The project is a joint program between BNL and Energy Consultants International (ECI), Inc. ECI has performed a multitude of economic feasibility studies for the national and international refining industry as well as funding institutions [International Monetary Fund (IMF), etc.]. ECI's extensive worldwide experience in marketing and oil processing has been applied in the biochemical processes evaluation of domestic and other heavy crudes used by the U.S. industry.

2. Background

During the past several years, a considerable amount of work has been carried out showing that microbially enhanced oil recovery (MEOR) is promising and the resulting biotechnology may be deliverable. At Brookhaven National Laboratory (BNL), systematic studies have been conducted which dealt with the effects of thermophilic and thermoadapted bacteria on the chemical and physical properties of selected types of crude oils at elevated temperatures and pressures. Particular attention was paid to heavy crude oils such as those form Venezuela, California, and those from Alabama, Arkansas, Wyoming, Alaska, and other oil producing areas. Current studies indicate that during the biotreatment several chemical and physical properties of crude oils are affected. The oils are (1) emulsified; (2) acidified; (3) there is a qualitative and quantitative change in light and heavy fractions of the crudes; (4) there are chemical changes in fractions containing sulfur compounds; (5) there is an apparent reduction in the concentration of trace metals; and (6) the qualitative and quantitative changes appear to be microbial species dependent; and (7) there is a distinction between "biodegraded" and "biotreated" oils. The former is more suitable for changes which occur under natural conditions over geological periods of time, and the latter is more applicable to changes brought about by deliberately introduced microorganisms acting over short periods of time and controlled conditions. Further, preliminary results indicate that the introduced microorganisms may become the dominant species in the bioconversion of oils. These studies have also generated information which supports the view that the biochemical interactions between crude oils and microorganisms follow distinct trends, characterized by a group of chemical markers. Such markers are useful in the prediction of bioprocessing efficiency prior to core-flooding experiments and field testing. Core-flooding experiments based on these predictions have shown that compared to commonly used microorganisms, e.g. <u>Clostridium</u> sp., significant additional crude oil recoveries are achievable due to the biochemical action of thermophilic (thermoadapted) microorganisms at elevated temperature similar to those found in oil reservoirs. In addition, the chemical and biochemical studies conducted at BNL have also shown that the biochemical treatment of crude oils has technological applications in downstream processing of crude oils such as in upgrading of low grade oils and the production of hydrocarbon based detergents.

3. FY 95 Publications, Reports, and Presentations

3.1 Premuzic, E.T., Lin, M.S., and Manowitz, B. The significance of chemical markers in bioprocessing of fossil fuels. Fuel Process. Technol. 40, 227-239 (1994). (BNL #49272).

3.2 Premuzic, E.T., and Lin, M.S. Applications of biochemical interactions in fossil fuels. Presented at the Minerals Bioprocessing II Conference, Snowbird, July 10-15, 1994.

3.3 Premuzic, E. T. and Lin, M. S. Chemical characterization of biotreated fossil fuels. Proc. Microbial Degradation and Modification of Hydrocarbons, Washington, Aug. 1994, Vol. 34(4) pp. 652-654, ACS Symposia, 1994. (BNL #60243).

3.4 Lin, M. S. and Premuzic, E. T. Biochemical processing of heavy oils and residuum. Presented at the Seventeenth Symposium on Biotechnology for Fuels and Chemicals, Vail, May 7-11, 1995. (BNL #61265). Also published in Appl. Biochem. and Biotechnol., Vol. 57/58, 659-664 (1996).

3.5 Premuzic, E. T., Lin, M. S., Lian, H. Bioconversion of heavy crude oils: A basis for new technology. Proc. The Fifth International Conference on Microbial Enhanced Oil Recovery and Related Biotechnology for Solving Environmental Problems, Dallas, Sep. 1995, R. Bryant, Editor, pp. 235-242 (1995). (BNL #61485).

3.6 Premuzic, E. T. Lin, M. S., Lian, H., Zhou, W.M., and Yablon, J. Microbial interactions in crude oils: Possible impact of biochemical versatility on the Choice of microbial candidates. Proc. The Fifth International Conference on Microbial Enhanced Oil Recovery and Related Biotechnology for Solving Environmental Problems, Dallas, Sep. 1995, R. Bryant, Editor, pp. 551-569 (1995). (BNL #61486).

A cumulative list of all publications, reports, etc. dealing with the Biochemical Treatment of Fossil Fuels is enclosed in Appendix B.

Patents

Premuzic, E.T. and Lin, M.S. Biochemically Enhanced Oil Recovery and Oil Treatment. U.S. Patent No. 5,297,625 (1994).

Premuzic, E.T. and Lin, M.S. Process for Producing Modified Microorganism for Oil Treatment at High Temperatures, Pressures, and Salinity (1996).

Two additional patents are pending. Associated Universities Inc. (AUI) has taken title to the inventions developed under this research program, has filed U.S. patent applications on these inventions which are pending before the U.S. Patent Trademark Office, and has initiated an act of licensing program aimed at commercializing these technologies

CRADA

Biochemical Production of Adsorbents from Fossil Fuel Wastes, University of Southern California.

4. Conclusions

Biochemical interactions between microorganisms and heavy crude oils and bituminous coals:

1. Are not Random
2. Follow distinct pathways which can be monitored by chemical markers
3. Match the utility and specificity of chemical markers used in oil exploration studies.

4. Depend on the chemical nature of the oil and/or coal and the particular biocatalyst used.

Thus, using chemical markers as diagnostic tools, the extent and the efficiency of fossil fuel bioconversion may be predicted and monitored, allowing for better cost-efficient field trials.

2. Depolymerization of the macromolecular structure has obvious applications in future refinery and coal liquefaction processes. The reduction of trace metals in fuel processes will extend the useful life of catalysts and consequently reduce operation costs. However, to develop a large volume process, bench experiments need to be scaled up to pilot plant scale processes, to gather parameters for the design reactor types, mixing rates, mass transfer and reaction rates needed for engineering and cost-efficiency evaluations.

3. Chemical markers representative of multiple biochemical processes, occurring during bioconversion of crude oils, serve as diagnostic tools by which the efficiency of fossil fuel bioconversion may be predicted and updated. Such monitoring is an important aspect in the development of new biochemical technology, as well as the evaluation of its efficiency and applicability.

4. Biochemical reactions leading to upgraded oils from mixtures as complex as crude oils are intricate and proceed via multiple inter- and intramolecular reactions involving depolymerization, desulfurization, denitrification, and demetalation pathways. Therefore, such biochemical reactions can be used to monitor the development of pretreatment processes applicable to crude oils in pipelines and storage tanks to save processing time and space. They may also be used for processing of downstream heavy fuels, residuum, and wastes in refineries.

Current studies at Brookhaven National Laboratory are focusing on scaled-up processing and extensive cost-efficiency analyses of processes based on the chemical changes in the heteroatom contents and the distribution of hydrocarbons. Preliminary results indicate that the emerging biochemical technology is promising and technically achievable.

Heavy oils, residuum, and oil wastes represent a substantial resource if a low-cost technology for their processing could be developed. In terms of reserves, 50-70% of original oil is still in place and is available. However, it is heavy and requires extensive secondary and tertiary recovery technology. Over the past few years at Brookhaven National Laboratory (BNL), we have been investigating biochemical processes for the treatment of heavy crude oils and heavy fractions of crude oils. Particular attention has been given to the interactions between extremophilic microorganisms (i.e., high temperature, pressure, salinity) and selected heavy oils. Significant biochemical conversions occur, leading to lighter oils. Recent advances in these studies have been presented and their significance discussed.

5. Ultimate success of any applicable process depends on its technical feasibility and its cost-efficiency. Use of chemical markers to evaluate the bioconversion of crude oils by microorganisms allows to monitor major variables characteristic of microbial action on crude oils. These include changes resulting in:

1. the composition of organic sulfur compounds;
2. the composition of nitrogen compounds;
3. the composition of organometallic compounds;
distribution of hydrocarbons.

In addition, the use of chemical markers allows to predict the cost-efficiency of a process and simultaneously guides the R&D effort in process optimization.

6. The use of chemical markers in the monitoring of the interactions between different microorganisms and various crude oils allows us to determine the efficiency of the biochemical conversion of the crudes. Concurrently a data base is generated which indicates that the

biochemical mechanisms by which microorganisms interact with crude oils involve reactions at heteroatoms, i.e. N, S, O, and organometallic compounds and other active sites leading to:

1. Reduction in sulfur concentration (20% - 45%)
2. Reduction in nitrogen concentration (15% - 45%)
3. Reduction in trace metals concentration (16% -45%)
4. Conversion of heavy fraction of crudes into lighter fractions
5. Optimum reaction conditions depend both an microbial species used and the chemical composition of the oil.

7. An independent economic analysis of the BNL Biochemical Upgrading of Petroleum process shows that the BNL process is technically feasible, economically cost-efficient, and complimentary to the existing chemical upgrading processes. Optimization of several process parameters contributes significantly to increases in the cost-efficiency of the overall process.

5. Recommendations for FY 96

1. Favorable economic analysis of the BNL-BUP process indicates that small improvements in any of the nineteen independent parameters, used in the engineering analyses, can tremendously increase the profitability of the process. Continued optimization of the BUP process with an R&D emphasis on heavier crude oils, market drivers, contaminant reductions, biocatalyst/crude oil ratios, biocatalyst cost, etc. is strongly recommended. Minor process improvements in nineteen leading parameters can lead to greater net realization and will significantly encourage technology transfer.
2. Additional BUP process improvements and analyses of the environmental impacts of BUP Produced Water (PW) is recommended; to mitigate environmental concerns, enhance BUP technology integration, and improve the process economics. Emerging environmental regulations, national and international, offer opportunity for the BUP process to be considered

as a Best Available Technology with downstream petroleum processing cost avoidance benefits.

3. Expanded testing of heavier crude oils, with emphasis on domestic refinery mixtures, is recommended to develop industry-specific test results. The relationships between BUP biocatalysts and refinery feedstocks affect distillation fractions and product targets. BUP test results and process data need to be developed to validate domestic/international operational experience.
4. Collaborative R&D efforts with the petroleum industry to assess and optimize the opportunities for BUP technology intervention in both upstream and downstream processes is recommended. Scaling-up of the BUP engineering requirements and economic model(s) are governed by industry site-specific criteria and environmental conditions, e.g. onshore/offshore. Validation by proprietary industrial models used for economic and engineering analyses are vital to BUP technology deployment.
5. Collaborative agreements between industry and government in the technology transfer and cost sharing of scaling-up to demonstration and/or pilot plant size is recommended. Industry participation, motivated by profit and proprietary interests, is vital to BUP technology implementation that is consistent with national interests.
6. Expansion of the BUP R&D testing to examine waste oils is recommended. Waste oils approximate 400 million gallons annually, and oil recovery coupled with environmental mitigation opportunities are of national interest. R&D efforts are necessary to understand the complexity of interactions between heavy oils and biocatalysts.
7. Identification of a mechanism(s) e.g. establishment of a technology transfer company, industry agreements, cost-sharing efforts, etc. are recommended to facilitate the transfer of applicable

BUP technology to the private sector. National interest in reducing dependency upon oil imports, supporting environmental regulatory goals and regaining domestic refining capabilities require petroleum industry participation that is motivated by clean, cost-effective technology introduction.

8. Continued developments and expansion of a database that characterizes the biochemical mechanisms by which biocatalysts interact is recommended. Technology transfer is based upon the sharing of experimental data with the private sector. Industry requires data that are precise, characteristic, and complete in an automated form that permits independent validation.
9. Extension of the BNL-ECI economic model to assess costs and net realization for industrial-size BUP application(s) e.g. 50 MBD is recommended. Economic models need to reflect industry operational conditions and be capable of processing variable processing conditions, e.g. changes in flow rates, process variabilities, etc.

Appendix A

Economic Feasibility of Biochemically Upgrading of Heavy Crudes, submitted Energy Consultants International, Ltd., June 1995.

Appendix B

Cumulative list of all publications, reports, and presentations dealing with Biochemical Treatment of Fossil Fuels..

APPENDIX A

ECONOMIC FEASIBILITY OF BIOCHEMICALLY UPGRADING HEAVY CRUDES

Economic Feasibility of Biochemically Upgrading Heavy Crudes

BNL Contract 725009

Final Report

Submitted To

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June, 1995

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Acronyms

A	Surface Area of Filter Press or Intercept of Linear Eqn. ($y = A + Bx$)
AH	Arabian Heavy
AHVR	Arabian Heavy Vacuum Residue
AIR	Additional Investment Requirements
AL	Arabian Light
ANS	Alaskan North Slope
AP	Aqueous Phase Processed Through the Precipitation Drum/Batch
APFR	Aqueous Phase Flow Rate Into Precipitation Drum
ASPH	Asphaltenes ($/yr)
$ASPH_u$	Unit Cost of Asphaltenes ($/bbl)
B	Slope of Linear Equation ($y = A + Bx$)
$B_{0\text{-}10}(V)$	"Bullet 0-10 barg" Empirical Functional Relationship of Purchased Equipment Cost, C_p, to Volume, V
BC	Bacterial Culture/batch
BF	Bioreactor Fluids/batch
BFW	Boiler Feed Water cost per year
BFW_u	Unit Cost of Boiler Feed Water ($/Mgal)
BLE	Battery Limit Process Equipment Costs
BPC	By-Product Credits
BPT	Bioreactor Processing Time
BPY	Number of Process Batches Per Year
BTPT	Batch Total Processing Time
C	Cost of New York Cargo Resid Fuel Oil Per Barrel
C^A_{BM}	Purchased Cost (1993) of Precipitation Drum Agitator
CAT	Catalysts
CATCAN	Cat Canyon (California Heavy) Crude Oil
C_{BM}	Bare Module Equipment Cost
CC	Annual Capital Charges
CC	FYPBBT
CCL	Canadian Cold Lake Crude Oil
CDHT	Catalysts for Distillate Hydrotreating
CEAI	Chemical Engineering Plant Cost Annual Index
CHM	Catalysts for Hydrogen Manufacture
C_p	Purchased Equipment Cost
$CP(p_i)$	"Centrifugal Pump" Empirical Functional Relationship of F_p to p_i

$CP(w_s)$	"Centrifugal Pump" Empirical Functional Relationship of C_p to w_s
CPB	Cycles Per Batch
$C^{PD}{}_{BM}$	Purchased Cost (1993) of Precipitation Drum, Including both Drum Vessel and Drum Agitator
CR	Total Credits of the BNL Process
CR(V)	"Cone Roof" Empirical Functional Relationship of C_p to V
CRU	Catalysts for Residue Upgrading
$C^{V}{}_{BM}$	Purchased Cost (1993) of Precipitation Drum Vessel
CW	Cooling Water cost per year
CW_u	Unit Cost of Cooling Water ($/Mgal)
D	Diameter of Motionless Mixer
DCF	After-Tax Discounted Cash Flow
E&HO	Engineering and Home Office Expense
E_a	Energy Consumed by the Agitator of the Precipitation Drum
ECE	Environmental Control Equipment Costs
E_ℓ	Energy Consumed for Lighting and Heating, Ventilation & Air Conditioning (HVAC) of the BNL plant
E_{p1}	Energy Consumed by Motor of Pump No.1
E_{p2}	Energy Consumed by Motor of Pump No.2
E_{SC}	Energy Consumed by Motor of Sedimentation Centrifuge
E_T	Energy Consumed by All Electric Systems of the Plant (Including Energy Losses Throughout the Circuits)
F_{BM}	Bare Module Factor; the Purchased Equipment Cost, C_p, multiplied by this factor yields the bare module cost, C_{BM}
FEEDA	Annual Oil Feedstock to the Upgrading Process
FEEDD	Daily Oil Feedstock to the Upgrading Process
FF	Filling Factor (Percentage of Total Volume Filled)
FG	Purchased Fuel Gas
FLBG	Flexicoker LBG ($/yr)
$FLBG_u$	Unit Cost of Flexicoker LBG ($/FOE bbl)
F_M	Material Factor; the ratio of purchased equipment cost, C_p, for an item constructed of a special alloy or material relative to the price of the same item constructed of carbon steel
FOB	Freight On Board
FOE	Fuel Oil Equivalent
F_P	Pressure Factor; The Ratio of the Cost of Equipment Designed for High Pressure Relative to the Cost of Conventional Equipment for Atmospheric Pressure
FYRPBBT	5-Year Payback Before Taxes
GF	Off-Site and General Facilities Cost ($/yr)
HHV	Higher Heating Value of Combustion
HO	Heavy Oil/batch

HPB	Hours Per Batch of Operation of a Motor
HPB_a	Hours Per Batch of Operation of Agidator of Precipitation Drum
HPB_{p1}	Hours Per Batch of Operation of Pump No. 1
HPB_{p2}	Hours Per Batch of Operation of Pump No. 2
HPB_{sc}	Hours Per Batch of Operation of Sedimentation Centrifuge
HPY	Hours Per Year of Operation of a Motor
HPY_a	Hours Per Year of Operation of Agitator of Precipitation Drum
HPY_{p1}	Hours Per Year of Operation of Pump No. 1
HPY_{p2}	Hours Per Year of Operation of Pump No. 2
HPY_{sc}	Hours Per Year of Operation of Sedimentation Centrifuge
IBP	Initial Boiling Point
IN	Insurance
KERNRIV	Kern River (Californian Heavy)
LB	Annual Labor Cost
LBG	Low Btu Gas
LM	Labor Maintenance Costs
LR	Labor Rate
lt	Long Ton
m	Mass Flow Rate Through a vessel
m_{ap}	Mass Flow Rate of Bacterial Aqueous Phase exiting the sedimentation centrifuge
MEXM	Mexican Maya
MLM(D)	"Motionless Mixer" Empirical Functional Relationship of C_p to diameter D
MM	Materials Maintenance Costs
MMT	Motionless Mixer Throughput
m_o	Mass Flow Rate of Oil Phase exiting the sedimentation centrifuge
m_{p2}	Mass Flow Rate Through Pump No. 2
$MPF(F_p \times F_m)$	"Material and Pressure Factors" Empirical Functional Relationship of Bare Module Factor, $F^a{}_{BM}$, to Material Factor and Pressure Factor for pumps
m_{ps}	Mass Flow Rate of Pumped Solution entering the sedimentation centrifuge
m_{sc}	Mass Flow Rate Through Sedimentation Centrifuge
MT	Maintenance
NG	Natural Fuel Gas
NR	Net Realization of a Process
NRB	Net Realization per Barrel of a Process
O_2	Oxygen ($/yr)
O_{2u}	Unit cost of Oxygen ($/st)
OC	Annual Operating Costs ($/yr)
OH	Annual Overhead Costs
OPC	Oil Product Credits

P	Power
PB	Payroll Burden
PC	Petroleum Coke ($/yr)
PC_{pm}	Percentage of Energy Consumed by all Plant Motors Equal to Energy Consumed for Lighting and HVAC
PC_u	Unit Credit of Petroleum Coke ($/st)
PDPT	Precipitation Drum Processing Time
PDT	Precipitation Drum Throughput
PF(A)	"Plate and Frame" Empirical Functional Relationship of Purchased Equipment Cost, C_p, to Surface Area, A, of Filter Press
PHS	Pitch (high sulfur)
P_i	Pump Suction Pressure
PLS	Pitch (low sulfur)
PR	Paid-Up Process Royalties
PRE	Amount of Precipitant/batch
PRFR	Precipitant Flow Rate Into Precipitation Drum
PRODO	Annual Amount of Product Oil in Barrels
PRODOT	Annual Amount of Product Oil in Metric Tons
PRODS	Annual Amount of Product Sulfur
PRT	Product Recovery Time
PSU	Plant Startup and Minor Revamps (or Retrofits)
PSUT	Plant Set-Up Time
PTPT	Property Taxes
PW	Annual Energy Consumed by Plant
PW_u	Unit Cost of Electric Energy ($/kWh)
q	Volumetric Flow Rate Through a vessel
RG	Refinery Fuel Gas
ROI	Rate Of Return on Total Capital Investment Per Current U.S. Tax Structure
RS	Removed Sulfur From Oil Into Bacterial Culture per Batch
S	Amount of Sulfur (wt%) or Simply Sulfur.
SB(P)	"Stuffing Box" Empirical Functional Relationship of Purchased Equipment Cost, C_p, to Pressure, P
SC(q)	"Sedimentation Centrifuge" Empirical Functional Relationship of Purchased Equipment Cost, C_p, to Volumetric Flow Rate, q
scf	Standard cubic feet, gas measured at 60°F, 1 atm pressure
S_{CR}	Selling Price of By-Product Sulfur
SCT	Sedimentation Centrifuge Throughput
SDPY	Stream Days Per Year of Operation of a Motor or Plant
SGAP	Specific Gravity of Aqueous Phase
SGOP	Specific Gravity of Oil Phase
SGPS	Specific Gravity of Pumped Solution Through a Vessel
SO	Shift Overlap
SPR	Sulfur Percent Removed from Heavy Oil by BNL Process

SPROD	Sulfur Weight Content in the Product Oil
SREM	Weight Percent of Product Oil Equal to Amount of Product Sulfur Removed
ST	Steam
st	Short Ton
SUP	Supervision
SWP	Sulfur Weight Percent in Heavy Oil Feed
TCIC	Total Capital Investment Costs
TFC	Total Facilities Costs
ton	Metric Ton
TPPT	Two-Plant Processing Time
UT	Utilities Cost ($/yr)
V	Volume of a Vessel
VB	Venezuelan Bachquero (VB)
VGO	Vacuum Gas Oil
WC	Working Capital
w_s	Power of a Motor at the Shaft
$w_{s,a}$	Power of Agitator of Precipitation Drum at the Shaft
$w_{s,p1}$	Power of Pump No.1 at the Shaft
$w_{s,p2}$	Power of Pump No.2 at the Shaft
$w_{s,sc}$	Power of Sedimentation Centrifuge at the Shaft
WTIM	West Texas Intermediate
ΔP	Differential Pressure Drop Through the Pump
ε_i	Intrinsic Efficiency of the Pump
η	Efficiency of Motors
ρ	Mass Density of the Fluid Pumped
ρ_o	Mass Density of Oil Phase
ρ_w	Mass Density of Water (=1,000 kg/m^3)

1

Executive Summary

1.1 Objectives

Brookhaven National Laboratory's (BNL) contract with Energy Consultants International Ltd, (ECI) had two objectives:

1. To identify the thresholds of economic performance of BNL's biochemical process for upgrading heavy crudes, and to assess which thresholds or "benchmarks" render the process economically competitive with current upgrading processes in oil refineries. According to the contract's scope of work, the costing methodology to be used for economic comparisons between BNL's process and chemical upgrading processes in operation in U.S. and foreign refineries must be the one used by SFA Pacific, Inc. (SFA) in its report "Upgrading Heavy Crude Oils and Residues to Transportation Fuels: Technology, Economics and Outlook -Phase IV" (please see List of References). Similarly, the benchmarks of economic performance must be taken from this SFA report.

2. To identify the requirements that must be met by applications (or proposals) for funding of related industrial projects so that the proposals can be considered by international funding institutions, such as The World Bank (WB), The Inter-American Development Bank (IADB), The European Investment Bank (EIB), (Luxembourg), The European Bank for Reconstruction and Development, (EBRD), (London), The Agency for International Development (AID), The Organization of American States (OAS), commercial banks such as Chase Manhattan, City Corp., Manufacturers Hanover, and international venture financing groups. BNL intends to enter joint R&D projects with U.S. oil refiners, U.S. electric utility corporations, foreign governments, and international financial concerns for industrial testing and demonstration of BNL's biochemical process for upgrading heavy crudes. Acquiring funding from such sources is very crucial for the construction and operation of an industrial facility capable of demonstrating the technical feasibility and economic attractiveness of the

process. BNL's and its partners will need to submit applications (or proposals) for funding the industrial energy projects to these international institutions. Therefore, a knowledge of their requirements on the required substance and format of proposals submitted to them is very critical for acceptance of BNL proposals for consideration.

1.2 Results

SFA uses Net Realization (NR) as its methodology for assessing and comparing the profitability of alternatives for processing a specific crude oil by a specific technology. SFA Pacific developed the concept for this application and has used it as such for several years. The NR is defined as the difference between the value of all of the products, less the cost of the crude oil and the cost of the processing operations, including a return on the capital cost of new facilities. NR is expressed in dollars per barrel of feed.

SFA calculated the net realization (NR) for 34 process-feed combinations by selectively applying its standard costing methodology on 17 chemical upgrading processes, when these processes treated 7 different types of oil feeds. SFA also made "summary" economic analyses for 5 additional process-feed combinations. These summary analyses are "broad-brush" economic calculations which did not produce NR results. Table 1-1 shows the SFA results. SFA used in its analysis Arabian Heavy as its basecase feed, i.e. the feed treated by all 22 processes considered in its study. The remaining 6 feeds each were treated only by 2 to 3 processes. The SFA-calculated NRs for the 34 process-feed combinations vary from -1.46 \$/bbl to 0.69 \$/bbl of processed feed. This variability is due to the differing degrees of severity of processing required for treating the 7 types of oil feeds examined. However, even when only the basecase feed is considered, i.e. the Arabian Heavy, there is still a variation from -1.46 to 0.69 in the NRs among the 17 processes.

For the SFA analysis, NR was arbitrarily adjusted to near zero (0.05 \$/barrel) for the case in which Arabian Light vacuum residue is treated by delayed coking. With the exception of delayed coking, specific types are not identified in order to preserve the proprietary nature of the overall SFA analysis. Processes included in the analysis, in addition to delayed coking, include:

Fixed-bed HDS
Flexicoking
Ebullated bed hydrocracking systems
Slurry phase hydrocracking systems
Fixed-bed hydrocracking

Visbreaking
Various combinations of the above conversion processes with solvent deasphalting
Residue gasification

Processes which yield better (more positive) NRs in treating some particular heavy crudes are generally used to upgrade them, even though their NR is less than the NR of others, for a variety of reasons. One main reason is no two processes yield products of identical make-up. The products on each occasion are required as feeds in the subsequent processing steps of a particular refinery. Another process may be more profitable in treating a certain heavy crude, but the products it generates may not be the ones desired by a refinery which, therefore, chooses to use a less profitable process. As long as the process is profitable, they attempt to use it, even when their profit margins are less than the profits of some of their competitors. Each refinery makes the most it can with the technology available, and constantly attempts to improve its technology.

The "thresholds" or "benchmarks" of economic performance that must be achieved by BNL's biochemical process so that it can successfully compete with any of the processes considered in the SFA study for upgrading any particular oil feed are the NR numbers given in Table 1-1.

The present work shows that the BNL process competes economically when it treats several types of feeds, although it does not do so well when it processes several others. The sensitivity analysis in Chapter 4 establishes a wide range of profitable applications of the BNL process, even at its present preliminary stage of development. Some of the applications yielding a positive net realization are summarized in Table 1-3.

ECI applied the SFA costing methodology on High-Sulfur Resid Fuel Oil with 3 wt% S, delivered at New York Harbor, to produce High-Sulfur Resid Fuel Oil with 2 wt% S as sole product, and elemental sulfur as the sole byproduct. This oil was chosen as the pilot feed for BNL's biochemical process because the BNL process already has attracted the interest of several U.S. electric utility companies, such as Long Island Lighting Company (LILCO), because a desulfurization process applied to High-Sulfur Resid Fuel Oil with 3 wt% S, towards production of such oil with 2 wt% S costs less than the latter at current market prices. Under its current technological efficiency at bench scale, the BNL process has a NR of 0.06 $/bbl, which is the smallest positive net realization among all the profitable applications of the BNL process discussed in Chapter 4. This economic performance is predicated on the set of numerical values of all the independent process parameters shown in Table 1-2. These values constitute the "Base Case" of process instrumentation and operating conditions.

The sensitivity analyses described in Chapter 4 prove that paramount improvements of the net realizations can be achieved with very modest improvements of the technological performance of the BNL process or the prevailing market conditions. These extremely impressive finding are summarized in Table 1-4 and Figure 1-1, which lists the independent parameters of the process in order of declining importance (i.e., the sensitivity of the dependence of the net realization on these independent parameters). The table reports the change of net realization as a result of a 10% change of the numerical value of each independent parameter over the value of the base case.

The greatest improvement of the net realization can be achieved with a 10% increase of the sulfur content in the crude oil feed. Indeed, if the Resid Fuel Oil processed by BNL process had 3.3% sulfur, instead of the 3.0% studied in the base case, then the net realization would improve by 364.7%, i.e., would increase from 0.06$/bbl to 0.28$/bbl! This improvement depends strictly on market conditions (availability of Resid Fuel Oil with 3.3% sulfur at the price dictated by the prevailing market-price curve). This economic parameter is independent of the technological effectiveness of the process.

The second most important independent parameter is the slope of the curve "Price of Crude vs. Sulfur Content of Crude." In other words, the sharper the price rises with drop in sulfur content, the sharper is the increase in net realization. A ten percent increase of the steepness of the price slope results at a whopping increase of 354.2% in the net realization, i.e. from 0.06$/bbl to 0.27$/bbl. This independent parameter depends also on market conditions, rather than on the technical effectiveness of the BNL process.

The third independent parameter is the percentage of sulfur removed from the feed as a result of BNL's biochemical treatment. If the percent of sulfur removed per batch is improved by 10%, i.e., is increased from the current 33.33% to 36.67%, then the net realization increases by 351.1%, i.e., from 0.06$/bbl to 0.27$.bbl! This independent parameter strictly reflects the process' technical effectiveness and is independent of market conditions. BNL can very easily improve the effectiveness to remove 36.67% of sulfur per batch from the currently achievable 33.33%. This very small technological improvement holds the greatest promise for economic improvement.

The fourth most important independent parameter is the volumetric ratio of the bacterial culture to the oil volume treated per batch. The BNL process currently uses a bacterial culture volume equal to 60% of the oil volume. It the volume of the culture needed were 54%, as opposed to the current 60%, i.e. if the process was more effective and needed 10% less culture to achieve the current results, then the net realization would go up by a huge 162.1%, i.e. it would increase from the current 0.06$/bbl to 0.16$/bbl.

The fifth most important independent parameter is the price of the bacterial culture. Should the purchase price of the culture go down by 10% over the current market price, i.e. should BNL have to pay 9$/m^3 instead of the 10$/m^3 paid now, then the net realization would go up by 160.5%, i.e. it would be 0.15$/bbl instead of the current 0.06$/bbl! To great extent, this parameter is controlled by the market. However, should BNL develop the technology for producing the bacterial cultures more cheaply and effectively than at present, then this parameter is not only market-controlled, but also dependent on technological development.

The sixth most important parameter is the batch processing time. If the processing time was reduced by 10%, i.e. dropped to 43.2 hrs/batch from the current level of 48 hrs/batch, then the net realization would increase by 157.8%! This is strictly a process dependent parameter. BNL can very effectively control this parameter with technological improvement in the process.

The seventh most important parameter is the amount of oil to be treated per batch, i.e. the plant size. A 10% percent increase in the volume of oil treated per batch from the current 250,000 gal of oil/batch to 275,000 gal of oil/batch would increase net realization by 138.9%. This is a parameter that depends on the availability of equipment and space.

The eighth most important parameter is the number of cycle per batch, i.e. the number of times that the oil-bacterial culture must be recycled through the bioreactor per batch. A ten percent decrease from the current 50 cycles per batch to 45 cycles would increase net realization by 121.0%. This also is a process dependent parameter (no market) that BNL can very easily improve.

The ninth most important parameter is the mass flow rate of the two pumps. At a fixed number of 50 cycles/batch, a 10% increase in the flow rate of the two pumps would substantially shorten the batch processing time and improve the net realization by 103.6%, i.e. from 0.06$/bbl to 0.12$/bbl! This is a process dependent parameter (no market).

The tenth most important parameter is the labor requirements. If the number of employees is reduced by 10%, to 1.8 as opposed to the current 2 employees, which means a few hours less than full time for either one or both of them, then the net realization increases by 96.2%, i.e. it almost doubles! This also is a process parameter. Very small improvements in automation can very easily substantially reduce labor requirements.

The eleventh most important parameter is the number of stream days per year, i.e. number of days per year that the plant operates and produces for 24 hrs. A 10% increase from the SFA-assumed 330 stream days per year to 363 sd/yr increases net realization by 72.6%, i.e. from 0.06$/bbl to 0.10$/bbl. This is not a market dependent parameter. It is dependent on the number of days that maintenance may be required. The loss of only two stream days per year may be unrealistic, but certainly there is room of improvement over 35 days down-time assumed by SFA.

ECI also studied the sensitivity of dependence of net realization on 8 additional, but much less important, independent parameters (Table 1-4). A 10% improvement in any of them gives less than 20% improvement in net realization.

1.3 Conclusions

Our key conclusion is that very small improvements in any of many independent parameters of the process can tremendously increase the profit.

1.4 Recommendations

We very enthusiastically recommend further strong R&D funding of the process, as it appears that it already has reached the brink of great financial achievements.

Table 1-1 Net Realization by Petrochemical Upgrading Processes According to SFA

Processes	Crude Feeds						
	Arabian Light	Alaskan North Slope	Arabian Heavy	Mexican Maya	Venez. Bacha-quero	Canad. Cold Lake	Vacuum Residue
Delayed Coking	0.05	0.29	(0.13)	0.06	(0.01)	0.09	0.64
Process - 1A			(0.22)	0.16	(0.14)	0.07	0.24
Process - 2A	0.11		(0.98)				
Process - 2B			(0.61)				
Process - 2C			(1.35)				
Process - 3A			(1.29)				
Process - 3B			(1.45)				
Process - 3C			(1.46)				
Process - 4A			(0.67)				
Process - 4B			(0.28)				
Process - 4C			0.03				
Process - 4D			(0.38)				
Process - 5A			(0.62)				
Process - 5B			(0.67)				
Process - 5C			(0.71)				
Process - 5D			(0.93)				
Process - 6A	0.14	0.63	0.04	(0.39)	(0.49)	(0.60)	(0.59)
Process - 7A			0.69				
Process - 8A			0.75				
Process - 9A			(0.31)				
Process - 9B			0.42				
Process - 10A				0.20			

Note: Values in parenthesis indicate negative quantities

Table 1-2 Base Case of BNL Process Instrumentation Choices and Operating Conditions

Process Parameter #	Process Parameter Name	Process Parameter Numerical Value
	BNL-Set Parametric Values	
1	Batch processing time	48 hrs
2	Temperature	30^o - 40^oC
3	Pressure	1 atm
4	Oil feed/batch	250,000 gal = 946 m^3 = 757 ton
5	Bacterial culture (0.6 of Feed)/batch	150,000 gal = 568 m^3 = 568 ton
6	Bacterial culture cost	\$10/m^3
7	Sulfur reduction per batch	33 wt%
8	Plant operator-year level of labor	2
9	Purchase cost of oil No.6 with 3 wt% sulfur (Process Feed)	$10.775/bbl
10	Sale price of oil No.6 with 2 wt% sulfur (Product Credit)	$12.70/bbl
11	Filling factor of bioreactor	80%
12	Number of recirculations of oil-bacterial solution into the bioreactor per batch	50 cycles
13	Pump No.1 flow rate	1,030 ton/hr
14	Pump No.2 Flow Rate	770 ton/hr
15	Pressure drop across Pump No.1	0.5 atm
16	Pressure drop across Pump No.2	0.5 atm
17	Oil-bacterial solution flow rate into sedimentation centrifuge	144 ton/hr
18	Precipitant flow rate into precipitation drum	1 ton/hr
19	Volume of precipitation drum	50,000 gal
20	Filter surface area	10 m^2
21	Diameter of motionless mixer	0.5 m
22	Efficiency of Pump No.1	0.6
23	Efficiency of Pump No.2	0.6
24	Construction material of bioreactor	Carbon Steel
25	Construction material of motionless mixer	Stainless Steel
26	Construction material of Pump No. 1	Carbon Steel
27	Construction material of Pump No. 2	Carbon Steel
28	Construction material of sedimentation centrifuge	Carbon Steel
29	Construction material of precipitation drum vessel	Carbon Steel
30	Construction material of precip. drum agitator	Stainless Steel
31	Type of agitator	Liquid-Liq., Mild, Turbine, Axial
32	Construction material of filter press	Polypropylene
33	Type of filter press	Plate and Frame

SFA-Set Parametric Values

34	Plant set-up time	2 hrs
35	Plant operator-year cost	$280,670
36	Stream days per year	330 sd/yr
37	Electric power cost	$0.05/kWh
38	Sale price of elemental sulfur (By-Product Credit)	$50/lt

ECI-Set Parametric Values

39	Type of feed	High-Sulfur Resid Fuel Oil at NY Harbor
40	Feed sulfur content	3 wt% S
41	Price of feed	$10.574/bbl
42	Method of computation of feed price	Least squares fit to prices reported in Platt's Oilgram Price Report, September 14, 1993
43	Slope of feed cost vs sulfur content curve	B = - 2.024 $/%S
44	Intercept of feed cost vs sulfur content curve	A = $16.646

Parametric Values Still to be Set by BNL

45 Economic benefits due to wt% reduction of N and O_2

46 Economic benefits due to wt% reduction of Ni, heavy metals, and trace elements

47 Economic benefits due to cracking hydrocarbons with chains longer than 20 carbons to hydrocarbons with shorter chains

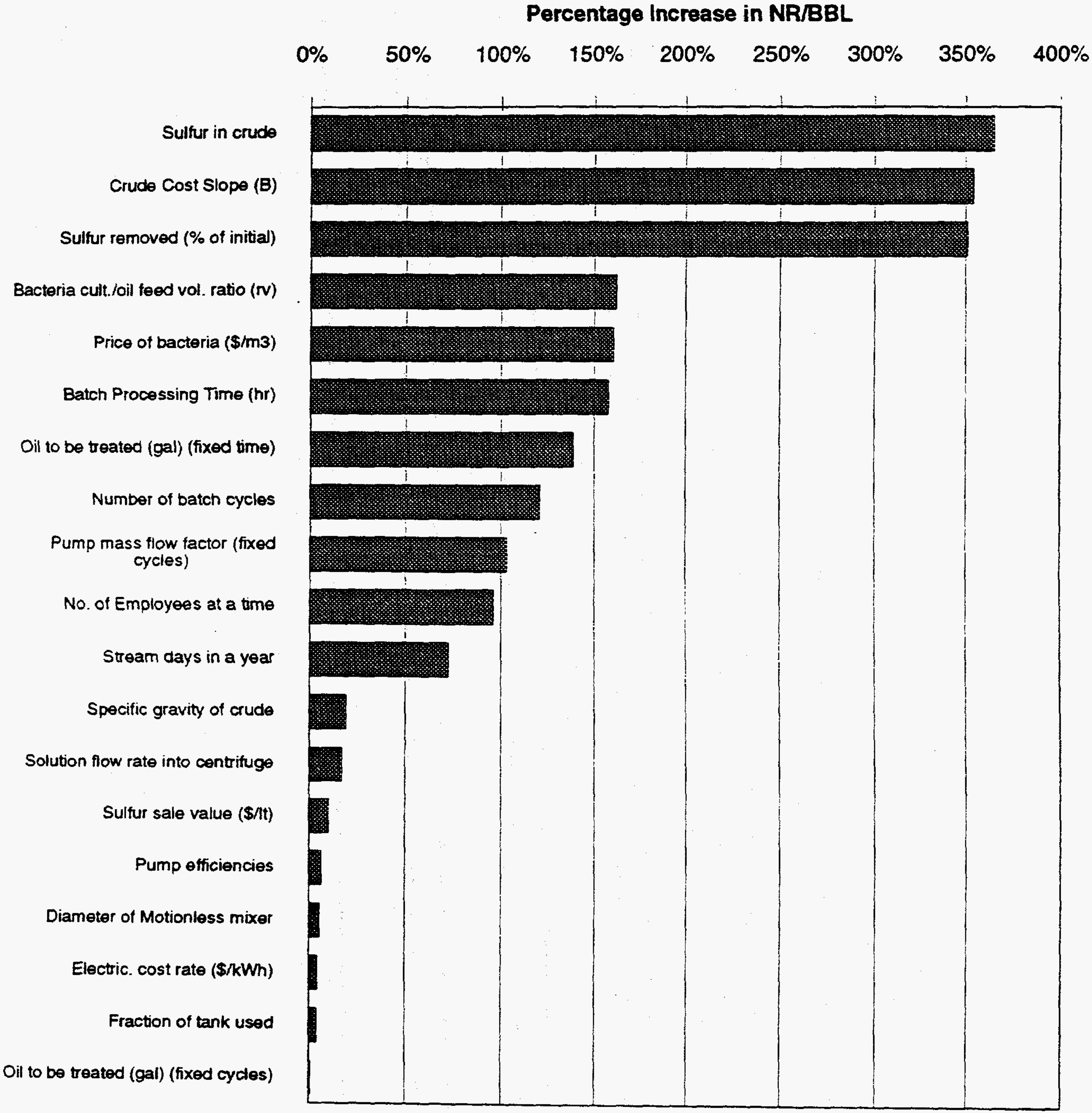
Table 1-3 Profitable Cases of Desulfurization of High-Sulfur Crudes by the BNL Biochemical Upgrading Process

Type of Crude Feed	Net Realization ($/bbl)
U.S. East Coast Residual Fuel Oil No.6 with 1.5%S, Consumer Tankcar, FOB Supplier's Rack, Delivered at Buffalo, N.Y.	1.765
U.S. East Coast Residual Fuel Oil No.6 with 1.3%S, Consumer Tankcar, FOB Supplier's Rack, Delivered at Buffalo, N.Y.	1.224
U.S. East Coast Residual Fuel Oil No.6 with 1.1%S, Consumer Tankcar, FOB Supplier's Rack, Delivered at Buffalo, N.Y.	0.682
Northwest Europe Oil No.6 with 3.0%S	0.386
U.S. East Coast Spot No.6 Cargo with 2.8%S	0.185
High-Sulfur Resid Fuel Oil with 3%S Delivered at N.Y. Harbor (Base Case of present report)	0.059

Table 1-4 Effect of ±10% Change of Input Parameters on the Net Realization For Resid Fuel Oil, Sep. 93 (All Other Input Parameters are as in the Base Case)

Input Parameter	Base value	New Value	($) New NR/bbl	% Change NR/bbl
Sulfur in crude	3.00%	3.30%	0.276	+364.7
Crude cost slope (B)	-2.0240	-2.2264	0.270	+354.2
Sulfur removed (% of initial)	33.33%	36.67%	0.268	+351.1
Bacteria cult./oil feed vol. ratio (rv)	0.60	0.54	0.156	+162.1
Price of bacteria ($/m3)	$10.00	$9.00	0.155	+160.5
Batch Processing Time (hr)	48	43.2	0.153	+157.8
Oil to be treated (gal) (fixed time)	250,000	275,000	0.142	+138.9
Number of batch cycles	50	45	0.131	+121.0
Pump mass flow factor (fixed cycles)	1	1.1	0.121	+103.6
No. of Employees at a time	2.0	1.8	0.117	+96.2
Stream days in a year	330	363	0.103	+72.6
Specific gravity of crude	0.80	0.88	0.071	+19.7
Solution flow rate into centrifuge	144	158.4	0.070	+17.3
Sulfur sale value ($/lt)	$50.00	$55.00	0.066	+10.5
Pump efficiencies	0.6	0.66	0.063	+6.5
Diameter of motionless mixer	0.5	0.45	0.063	+5.9
Electric. cost rate ($/kWh)	$0.05	$0.045	0.062	+4.6
Fraction of tank used	0.8	0.88	0.062	+4.5
Oil to be treated (gal) (fixed cycles)	250,000	275,000	0.060	+1.0

Figure 1-1 Bar Diagram of the Effect of ± 10% Change in the Input Parameters on the Net Realization



2

Computational Basis

This section describes the computational procedure followed in estimating the process net realization. A numerical example, using the base case data, in Table 2-1, illustrates the details of the calculation .

Section 2.1 describes the components of SFA costing methodology. Some components included in the SFA methodology are not used in the BNL process. For example, BNL does not use oxygen or steam. Nevertheless, Section 2.1 discusses all the components of SFA, even when they are not used in the BNL process. In Section 2.4, a numerical example for the BNL process is given. In this example, the parameters are those of the Base Case, shown in Table 1-2. Section 2.3 describes how we estimated the cost of equipment for the BNL process, following the methodology recommended by Ulrich. Section 2.2 describes some details of the kinetics of BNL's process .

The numerical examples shown in Sections 2.3 and 2.4 were calculated with a simple hand-calculator, while, in Section 3, the calculation was performed with MS EXCEL, using the same input parameters as the Base Case. There are some minor differences between results from the two methods because EXCEL performs all calculations with double precision, and displays the results in the format chosen by the user; in the hand-calculations the intermediate results often are recorded to fewer significative digits, and these results were used in subsequent calculations. However, despite the very small differences in the intermediate results, the manual calculations of Section 2 and the EXCEL calculations of Section 3 produced identical Net Realizations for the Base Case, i.e. 0.06 $/bbl.

2.1 Computing Process Net Realization on the Premises of the SFA Costing Methodology

2.1.1 Total Capital Investment Costs (TCIC)

The total costs of capital investment include the following ones:

- Total Facilities Costs (TFC)

- Engineering and Home Office Expenses (E&HO)
- Plant Startup and Minor Revamps (or Retrofits) (PSU)
- Paid-Up Process Royalties (PR)
- Working Capital (WC)

$$\boxed{TCIC = TFC + E\&HO + PSU + PR + WC} \quad (2\text{-}1)$$

2.1.2 Total Facilities Costs (TFC)

The following are the total facilities costs:

- Battery Limit Process Equipment (BLE)
- Utilities (UT)
- Off-Site and General Facilities (GF)

$$\boxed{TFC = BLE + UT + GF} \quad (2\text{-}2)$$

2.1.3 Battery Limit Process Equipment Costs (BLE)

These costs are based on the following indicators:

- BNL's (licenser) estimates
- User's estimates
- ECI in-house cost database
- Literature on costing and estimating chemical and petrochemical process equipment, facilities, and pilot plants
- 10% contingency burden on all process units

$$\boxed{BLE = 1.1 \times \{\text{Production Equip.} + \text{Environm. Controls Equip.}\}} \quad (2\text{-}3)$$

2.1.4 Environmental Control Equipment Costs (ECE)

They are part of the costs of the battery limit process equipment. There is no additional contingency burden over the 10% burden for all process equipment.

2.1.5 Off-Site & General Facilities Costs (GF)

Off-Site and General Facilities Costs are estimated at 35% of the costs of battery limits process equipment. They include the following items:

- Site preparation
- Buildings
- Shops
- Roads
- Tankage
- Spares
- Control Rooms
- Sewers

- Settling Ponds
- Safety Facilities

$$\boxed{GF = 0.35 \times BLE} \qquad (2\text{-}4)$$

2.1.6 Additional Investment Requirements (AIR)

- 10% of Total Facilities Costs for Engineering and Home Office Expenses (E&HO)
- 5% of Total Facilities Costs for Plant Startup and Minor Revamps (or Retrofits) (PSU)
- 2% of Total Facilities Costs for Paid-Up Process Royalties (PR)

$$\boxed{E\&HO = 0.10 \times TFC} \qquad (2\text{-}5)$$

$$\boxed{PSU = 0.05 \times TFC} \qquad (2\text{-}6)$$

$$\boxed{PR = 0.02 \times TFC} \qquad (2\text{-}7)$$

2.1.7 Working Capital (WC)

The working capital for the process comprises the following items:

- 1% of Total Facilities Costs
- Cost for a 20-day supply of crude oil (or residue oil) feedstock per day (FEEDD)

$$\boxed{WC = 0.01 \times TFC + 20 \times FEEDD} \qquad (2\text{-}8)$$

2.1.8 Operating Costs (OC)

The operating costs include the following items:

- Feedstock per year (FEEDA)
- Purchased Fuel Gas (FG)
- Utilities (UT)
- Catalysts (CAT)
- Labor (LB)
- Maintenance (MT)
- Overheads (OH)
- Property Taxes (PT)
- Insurance (IN)
- Capital Charges (CC)

$$\boxed{OC = FEEDA + FG + UT + CAT + LB + MT + [OH + PT + IN] + CC} \qquad (2\text{-}9)$$

2.1.9 Crude Oil & Residue Oil Feedstock Costs ($/bbl)

• Cat Canyon (Californian Heavy) (CATCAN)	8.00	(2-10)
• Arabian Heavy Vacuum Residue (AHVR)	9.00	(2-11)
• Canadian Cold Lake (CCL)	11.90	(2-12)
• Kern River (Californian Heavy) (KERNRIV)	13.50	(2-13)
• Venezuelan Bachaquero (VB)	13.70	(2-14)
• Mexican Maya (MEXM)	14.90	(2-15)
• Alaskan North Slope (ANS)	16.00	(2-16)
• Arabian Heavy (AH)	16.20	(2-17)
• Arabian Light (AL)	17.60	(2-18)
• West Texas Intermediate (WTIM)	19.00	(2-19)

2.1.10 Natural Fuel Gas (NG)

$$NG = \$2.50/MMBtu \qquad (2\text{-}20)$$

2.1.11 Refinery Fuel Gas (RG)

$$RG = \$2.50/MMBtu \qquad (2\text{-}21)$$

2.1.12 Low Btu Gas (LBG)

$$LBG = \$1.60/MMBtu \qquad (2\text{-}22)$$

$$LBG = \$10.00/FOE\ bbl \qquad (2\text{-}23)$$

$$FOE = \text{Fuel Oil Equivalent} = 6.3 \times 10^6\ \text{Btu HHV} \qquad (2\text{-}24)$$

where HHV = Higher Heating Value (of Combustion)

2.1.13 Utilities Cost (UT)

The utilities cost include the following items:

- Electric power cost per year (PW)
- Steam cost per year (ST)
- Oxygen cost per year (O_2)
- Boiler feed water cost per year (BFW)
- Cooling water cost per year (CW)

$$\boxed{UT = PW + ST + O_2 + BFW + CW} \qquad (2\text{-}25)$$

The unit cost of each form of energy above are:

$$PW_u = 0.05\ \$/kWh \tag{2-26}$$

$$ST_u = 5.00\ \$/Mlb \tag{2-27}$$

$$O_{2u} = 35\ \$/st \tag{2-28}$$

$$\boxed{1\ st = short\ ton = 2{,}000\ lb = 907\ kg} \tag{2-29}$$

$$BFW_u = 1.00\ \$/Mgal \tag{2-30}$$

$$CW_u = 0.10\ \$/Mgal \tag{2-31}$$

where

PW_u = Electric energy unit cost (\$/kWh)
ST_u = Steam unit cost (\$/Mlb)
O_{2u} = Oxygen unit cost (\$/st)
BFW_u = Boiler feed water unit cost (\$/Mgal)
CW_u = Cooling water unit cost (\$/Mgal)

2.1.14 Catalysts (CAT)

Typical types of catalysts are given below:

- Catalysts for Distillate Hydrotreating (CDHT)
- Catalysts for Hydrogen Manufacture (CHM)
- Catalysts for Residue Upgrading (CRU)

$$CDHT = 0.07\ \$/bbl \tag{2-32}$$

$$CHM = 0.06\ \$/Mscf \tag{2-33}$$

2.1.15 Labor Costs (LB)

Labor costs include the following items:

- Labor Rate (LR)
- Supervision (SUP)
- Payroll Burden (PB)
- Shift Overlap (SO)

$$LR = 18.00\ \$/hr \tag{2-34}$$

$$SUP = 0.20 \times LR \tag{2-35}$$

$$PB = 0.35 \times \{LR+SUP\} = 0.42 \times LR \tag{2-36}$$

$$SO = 0.10 \times \{LR+SUP+PB\} = 0.16 \times LR \tag{2-37}$$

$$LB = LR + SUP + PB + SO = 1.78 \times LR \quad (2\text{-}38)$$

$$LR\ Hours / \{Plant\ Operator\text{-}Year\} = 8{,}760\ hrs \quad (2\text{-}39)$$

$$LB / \{Plant\ Operator\text{-}Year\} = 1.78 \times 8{,}760 \times 18 = \$280{,}670 \quad (2\text{-}40)$$

2.1.16 Maintenance (MT)

Maintenance costs include the following items:

- Labor Maintenance costs (LM)
- Materials Maintenance costs (MM)

$$\boxed{MT = LM + MM} \quad (2\text{-}41)$$

$$\boxed{MT = 0.02 \times TCIC} \quad (2\text{-}42)$$

2.1.17 Annual Overhead (OH), Property Taxes (PT), and Insurance (IN)

$$\boxed{[OH + PT + IN] = 0.04 \times \{TCIC - WC - PR\}} \quad (2\text{-}43)$$

2.1.18 Capital Charges (CC)

$$\boxed{CC = 0.20 \times TCIC} \quad (2\text{-}44)$$

$$\boxed{CC = FYPBBT} \quad (2\text{-}45)$$

where FYPBBT = 5-Year Payback Before Taxes

$$\boxed{CC = 12\%\ DCF/ROI} \quad (2\text{-}46)$$

and where DCF/ROI = After-Tax Discounted Cash Flow Rate of Return on Total Capital Investment Per Current U.S. Tax Structure

2.1.19 Byproduct Credits (BPC)

The following credits were included for the process:

- Sulfur credit (S_{CR})
- Flexicoker LBG (FLBG)
- Petroleum Coke (PC)
- Pitch (low sulfur) (PLS)
- Pitch (high sulfur) (PHS)
- Asphaltenes (ASPH)

The subscript u is used to indicate unit price or cost, so that S_u represents the credit of selling one unit of Sulfur. For example:

$$S_u = 50\ \$/\mathrm{lt} \tag{2-47}$$

is the credit obtained by selling one long ton of Sulfur. The total credit from selling all the Sulfur produced in one year is S_{CR}. It is computed simply by multiplying S_u by the number of units produced in one year.

We recall that

$$\boxed{1\ \mathrm{lt} = \mathrm{long\ ton} = 2{,}240\ \mathrm{lbs} = 1{,}016\ \mathrm{kg}} \tag{2-48}$$

Similarly,

$$FLBG_u = 10\ \$/\mathrm{FOE\ bbl} \tag{2-49}$$

$$PC_u = 5.00\ \$/\mathrm{st} \tag{2-50}$$

This is a FOB price and actually may be a negative credit to the refiner, depending upon cost of loading freight on board of cargo ships

$$PLS_u = 10\ \$/\mathrm{bbl} \tag{2-51}$$

When the sulfur content is lower than 2 wt%

$$PHS_u = 5\ \$/\mathrm{bbl} \tag{2-52}$$

$$ASPH_u = 20\ \$/\mathrm{st} = 4.60\ \$/\mathrm{bbl} \tag{2-53}$$

2.1.20 Conversion Unit Product Prices

The following are the prices for the virgin IBP/650°F (342°F) and for the upgraded C_5/VGO products, so that the net realization of the delayed coking of Arabian Light crude is approximately zero:

$$\mathrm{IBP}/650°\mathrm{F\ at\ 20\ °API\ liquid\ gravity} = 20\ \$/\mathrm{bbl} \tag{2-54}$$

$$\mathrm{IBP}/650°\mathrm{F\ at\ 30\ °API\ liquid\ gravity} = 21\ \$/\mathrm{bbl} \tag{2-55}$$

$$\mathrm{IBP}/650°\mathrm{F\ at\ 40\ °API\ liquid\ gravity} = 21.8\ \$/\mathrm{bbl} \tag{2-56}$$

$$\mathrm{IBP}/650°\mathrm{F\ at\ 50\ °API\ liquid\ gravity} = 22.5\ \$/\mathrm{bbl} \tag{2-57}$$

where IBP/650°F = Virgin cut at initial boiling point of 650°F (342°F)

$$C_5/\mathrm{VGO\ at\ 20\ °API\ liquid\ gravity} = 21\ \$/\mathrm{bbl} \tag{2-58}$$

$$C_5/\mathrm{VGO\ at\ 30\ °API\ liquid\ gravity} = 22.8\ \$/\mathrm{bbl} \tag{2-59}$$

$$C_5/\text{VGO at 40 °API liquid gravity} = 24.5\ \$/\text{bbl} \qquad (2\text{-}60)$$

where C_5/VGO = C_5 Vacuum Gas Oil upgraded cut

2.1.21 Credits (CR)

The credits include the following:

- Oil Product (Conversion Unit Product) Credits (OPC)
- Byproduct Credits (BPC)

$$\boxed{CR = OPC + BPC} \qquad (2\text{-}61)$$

2.1.22 Net Realization (NR)

$$\boxed{NR = CR - OC} \qquad (2\text{-}62)$$

2.2 BNL Process Kinetics And Flow Rates

BNL's biochemical heavy-oil upgrading process is divided into two distinct parts. In the first section is the Biochemical Batch Process Plant (Figure 2-1) in which the heavy oil and the bacterial culture are introduced into the bioreactor as two separate phases. The aqueous bacterial culture being the heavier of the two phases precipitates to the bottom of the bioreactor, while the lighter oil phase floats to the top. The two phases are emulsified by being passed by two pumps through a motionless mixer. Pump 1 draws the aqueous bacterial culture into the mixer, while pump 2 draws the oil phase into the mixer (Figure 2-2). The two phases are emulsified progressively into one phase as they are recycled 50 cycles through the bioreactor-pumps-motionless mixer. On the basis of preliminary experimental runs, 50 cycles were found to be adequate to thoroughly emulsify most types of heavy crudes with the bacterial culture, and to complete bacterial desulfurization of the crude.

2.2.1 Bioreactor Fluid Content Per Batch

The total amount of fluids in the bioreactor is:

$$\boxed{BF = HO + BC} \qquad (2\text{-}63)$$

where:

BF = Bioreactor Fluids/batch
HO = Heavy Oil/batch
BC = Bacterial Culture/batch

In the Base Case (Table 1-2, Figure 2-1):

$$BF = 757 + 568 = 1325 \text{ ton/batch} \tag{2-64}$$

2.2.2 Bioreactor Emulsification And Desulfurization Time Per Batch

The total amount of time required for complete emulsification and desulfurization into the bioreactor is:

$$\boxed{BPT = [BF/MMT] \times CPB} \tag{2-65}$$

where:

BPT = Bioreactor Processing Time
MMT = Motionless Mixer Throughput
CPB = Cycles Per Batch

In the Base Case (Table 1-2, Figure 2-1):

$$\begin{aligned} BPT &= [\{1325 \text{ ton/batch}\}/\{1800 \text{ ton/hr}\}] \times 50 = \\ &= [0.736 \text{ hr/batch}] \times 50 = 36.8 \text{ hrs/batch} \end{aligned} \tag{2-66}$$

2.2.3 Sedimentation Centrifuge De-Emulsification and Product Oil Recovery Time

The second section of the BNL plant is the product recovery and waste processing plant. The fully emulsified, single-phase mixture of oil and bacterial culture is fed into a de-emulsification or phase-separation device. The device chosen used at present is a sedimentation centrifuge which separates the oil from the aqueous bacterial solution. One third of the sulfur content by weight in the oil has been removed in the bioreactor, and leaves the centrifuge absorbed in the aqueous bacterial solution.

The total amount of time needed for de-emulsification of the single-phase solution and recovery of the oil is:

$$\boxed{PRT = BF/SCT} \tag{2-67}$$

where:

PRT = Product Recovery Time
SCT = Sedimentation Centrifuge Throughput

In the Base Case (Table 1-2, Figure 2-1):

$$PRT = [1325 \text{ ton/batch}]/[144 \text{ ton/hr}] = 9.2 \text{ hr/batch} \qquad (2\text{-}68)$$

2.2.4 Amount of Aqueous Phase Fed from Sedimentation Centrifuge Into Precipitation Drum Per Batch

The bacterial aqueous phase impregnated with 33% of the sulfur in the feed oil is fed from the sedimentation centrifuge into a precipitation drum to which a precipitant, such as lime has been added. The precipitant becomes chemically bound to the sulfates, heavy metals and trace elements in solution and co-precipitates with them from the aqueous phase in the form of a cake onto the filter press.

The following is the amount of aqueous phase fed from the sedimentation centrifuge into the precipitation drum per batch:

$$\boxed{AP = BC + RS} \qquad (2\text{-}69)$$

where:
AP = Aqueous Phase Processed Through the Precipitation Drum/Batch
BC = Bacterial Culture/Batch
RS = Removed Sulfur From Oil Into Bacterial Culture/Batch

$$\boxed{RS = HO \times SWP \times SPR} \qquad (2\text{-}70)$$

where:
SWP = Sulfur Weight Percent in Heavy Oil Feed
SPR = Sulfur Percent Removed from Heavy Oil by BNL process

In the Base Case (Table 1-2, Figure 2-1):

$$\begin{aligned} AP &= 568 \text{ ton/batch} + 757 \text{ ton/batch} \times 0.03 \times 0.33 \\ &= 575.49 \text{ ton/batch} \end{aligned} \qquad (2\text{-}71)$$

2.2.5 Processing Time of Aqueous Phase in Precipitation Drum

The total processing time of the Aqueous Phase in the Precipitation Drum is:

$$\boxed{PDPT = [AP + PRE]/PDT} \qquad (2\text{-}72)$$

where:
PDPT = Precipitation Drum Processing Time

PRE = Amount of Precipitant/Batch
PDT = Precipitation Drum Throughput

$$\boxed{PRE = AP \times [PRFR/APFR]} \qquad (2\text{-}73)$$

and where:
PRFR = Precipitant Flow Rate Into Precipitation Drum
APFR = Aqueous Phase Flow Rate Into Precipitation Drum

Substituting PR from eqn. 2-73 into eqn. 2-72 yields:

$$\boxed{PDPT = AP \times [1 + PRFR/APFR] \; / \; PDT} \qquad (2\text{-}74)$$

In the Base Case (Table 1-2, Figure 2-1):

$$PDPT = 575.49 \text{ ton/batch} \times [1 + \{1\text{ton/hr}\}/62.5\{\text{ton/hr}\}] \; / \; 63.5 \text{ ton/hr}$$
$$= 9.21 \text{ hr/batch} \qquad (2\text{-}75)$$

Equations 2-68 and 2-75 show that for every practical purpose the Product Oil Recovery Time (PRT) is equal to the Sulfur By-product Recovery Time (Precipitation Drum Processing Time, PDPT), i.e. :

$$\boxed{PRT = PDPT} \qquad (2\text{-}76)$$

2.2.6 Two-Plant Processing Time Per Batch

The sum of the processing time of the two plants is:

$$\boxed{TPPT = BPT + PRT = BPT + PDPT} \qquad (2\text{-}77)$$

where:
TPPT = Two-Plant Processing Time
BPT = Bioreactor Processing Time
PRT = Product Recovery Time
PDPT= Precipitation Drum Processing Time

In the Base Case (Table 1-2, Figure 2-1 and Equations 2-66, 2-68, and 2-75):

$$TPPT = 36.8 + 9.2 = 46 \text{ hrs} \qquad (2\text{-}78)$$

2.2.7 Batch Total Processing Time

BNL assumes that some additional time will be spent in setting up the plant and in the transition of operations from the first to the second section of the plant. Thus:

$$\boxed{BTPT = TPPT + PSUT} \tag{2-79}$$

where:
BTPT = Batch Total Processing Time
PSUT = Plant Set-Up Time

In the Base Case (Table 1-2, Figure 2-1):

$$BTPT = 46 \text{ hrs} + 2 \text{ hrs} = 48 \text{ hrs} \tag{2-80}$$

2.3 Cost Estimating of BNL Battery Limit Process Equipment (BLE) on the Premises of the Ulrich Equipment Cost Estimating Methodology - Numerical Example for Base Case

The SFA study (References, 5.1.1) does not provide a costing methodology for calculating the costs of the Battery Limit Process Equipment (BLE). For each one of the 34 process-feed scenarios cost by SFA (Table 1-2), the BLE costs are actual ones reported by the plants evaluated, rather than estimated costs; SFA studied actual plants and used their historic data rather than estimated figures. Therefore, ECI was left to its own devices in assessing BLE costs. ECI maintains a comprehensive costing database for almost all energy industries. However, so that we did not miss any of the latest developments in costing methodologies for petrochemical plants, we undertook a comprehensive literature search. The sources identified are listed in References, Sections 5.1.1 and 5.1.2. Of all the costing methodologies evaluated, that of Ulrich (References, 5.1.1) was found to be among the most comprehensive and accurate; therefore, we adopted it throughout for estimating the costs of BLE.

Ulrich's costs estimates are for the year of 1982. To update these costs we used the Chemical Engineering Plant Cost Annual Index.

2.3.1 Bioreactor

The bioreactor was cost-estimated as an "Oil Tank" made of carbon steel, with a cone roof. The volume of the tank required is calculated as the sum of the two liquid phases fed into the bioreactor divided by the filling factor, i.e.:

$$\boxed{V = BF / FF} \tag{2-81}$$

where:

V = Tank's volume
BF = Bioreactor Fluids/batch
FF = Filling Factor (or percentage of total volume filled)

Inserting BF from eqn. 2-63 into eqn. 2-81 yields:

$$\boxed{V = [HO + BC] / FF} \tag{2-82}$$

where:

HO = Heavy Oil/batch
BC = Bacterial Culture/batch

We assume that 80% of the tank is filled during the reaction. Therefore, the tank volume required is:

$$V = [250{,}000 + 150{,}000] \text{ gal} / 0.8 = 500{,}000 \text{ gal} \tag{2-83}$$

From conversion tables, such as in Perry & Chilton (References, 9.1.1), it is found that:

$$\boxed{1 \text{ gal} = 3.785411 \times 10^{-3} \text{ m}^3} \tag{2-84}$$

Substituting gallons from eqn. 2-84 into eqn. 2-83 yields:

$$V = 1{,}892.71 \text{ m}^3 \tag{2-85}$$

Ulrich's curve for the Cone Roof in his Fig. 5-61 (Fig. 2-3 in the present report) gives C_p as a functional relationship of V through the empirical curve for the Cone Roof. It can be denoted:

$$\boxed{C_p = CR(V)} \tag{2-86}$$

where:

C_p = Purchased equipment cost
CR(V) = "Cone Roof" Functional Relationship of C_p to V

for V equal to 1,892.71 m^3, the empirical curve for Cone Roof gives:

$$C_p = \$43{,}090 \quad (2\text{-}87)$$

This figure was found by measuring, with a ruler, the lengths of the coordinates in logarithmic scales of an enlarged print of Ulrich's Fig. 5-61. The same procedure was used to extract numerical figures out of all Ulrich's graphs in Chapter 2 of the present report. Ulrich's charts used in the present study were computerized in Chapter 3, and numerical figures were extracted from the charts directly by the computer costing model designed on Excel spreadsheet.

The insert table in Ulrich's Fig. 5-61 gives for Carbon Steel:

$$F_{BM} = 1.9 \quad (2\text{-}88)$$

The insert equation in Ulrich's Fig. 5-61 gives:

$$\boxed{C_{BM} = C_p \times F_{BM}} \quad (2\text{-}89)$$

Inserting C_p from eqn. 2-87 and F_{BM} from eqn. 2-88 into eqn. 2-89 yields:

$$C_{BM,1982} = \$43{,}090 \times 1.9 = \$81{,}871 \quad (2\text{-}90)$$

The Bare Module Cost for 1993 is:

$$\boxed{C_{BM,1982} = C_{BM,1982} \times [CEAI_{1993} / CEAI_{1982}]} \quad (2\text{-}91)$$

where:

CEAI = Chemical Engineering Plant Cost Annual Index

Chemical Engineering, June 1994, p.158 (References, 5.1.2), Figure 2-4 in the present report, reports:

$$CEAI_{1993} = 359.2 \quad (2\text{-}92)$$

Ulrich's Fig. 5-61, or Fig.2-1 in the present report, gives:

$$CEAI_{1982} = 315 \quad (2\text{-}93)$$

Eqn. 2-92 and eqn. 2-93 give:

$$[CEAI_{1993} / CEAI_{1982}] = 359.2 / 315 = 1.1403 \quad (2\text{-}94)$$

Eqn. 2-91 and eqn. 2-94 give:

$$C_{BM,1993} = C_{BM,1982} \times 1.1403 \qquad (2\text{-}95)$$

Inserting $C_{BM,1982}$ from eqn. 2-90 and eqn. 2-95 gives:

$$C_{BM,1993} = \$81{,}871 \times 1.1403 = \$93{,}359 \qquad (2\text{-}96)$$

2.3.2 Motionless Mixer

The motionless mixer was cost-estimated according to Ulrich's costing methodology (p.306, Fig. 5-41, Figure 2-5 in the present report). This Figure gives C_p as an empirical functional relationship of the diameter of the motionless mixer:

$$\boxed{C_p = MLM(D)} \qquad (2\text{-}97)$$

where:

C_p = MLM = "Motionless Mixer" Empirical Functional Relationship of C_p on the diameter of the motionless mixer

D = Diameter of Motionless Mixer

For a diameter of motionless mixer equal to 0.5 m, Fig. 5-41 gives:

$$C_p = \$13{,}264 \qquad (2\text{-}98)$$

The insert table of Fig. 5-41 for stainless-steel construction material gives:

$$F_{BM} = 2.9 \qquad (2\text{-}99)$$

where:

F_{BM} = Bare Module Factor

The insert equation of Fig. 5-41 gives:

$$\boxed{C_{BM} = C_p \times F_{BM}} \qquad (2\text{-}100)$$

where:

C_{BM} = Bare Module Cost

Inserting C_p from eqn. 2-98 and F_{BM} from eqn. 2-99 into eqn. 2-100 yields:

$$C_{BM} = \$13,264 \times 2.9 = \$38,465 \tag{2-101}$$

This value is for 1982, as all Ulrich's curves are based on 1982 costs. Inserting this value in eqn. 2-95 yields:

$$C_{BM,1993} = \$38,465 \times 1.1403 = \$43,862 \tag{2-102}$$

2.3.3 Pump No.1

The cost of Centrifugal Pump made of carbon steel was assessed according to Ulrich's costing methodology (p. 310, Fig. 5-49, Figure 2-6 in the present report).

Ulrich's eqn. 4-3 (p. 67) gives:

$$\boxed{w_s = \frac{q\Delta P}{\varepsilon_i}} \tag{2-103}$$

where:

w_s = Power at the pump shaft
q = Volumetric flow rate through the pump
ΔP = Differential pressure drop through the pump
ε_i = Intrinsic efficiency of the pump

The volumetric flow rate is converted to mass flow rate through:

$$\boxed{q = \frac{m}{\rho}} \tag{2-104}$$

where:

m = Mass flow rate through the pump
ρ = Mass density of the fluid pumped

Substituting the volumetric flow rate, q, from eqn. 2-104 into eqn. 2-103 yields:

$$\boxed{w_s = \frac{m\Delta P}{\rho\varepsilon_i}} \tag{2-105}$$

The mass density of the fluid pumped, ρ, is expressed in terms of specific gravity by:

$$\boxed{\rho = SGPS\,\rho_W} \tag{2-106}$$

where:

SGPS = Specific gravity of pumped solution
ρ_W = Mass density of water

Substituting the mass density of the fluid pumped, p, from eqn. 2-106 into eqn. 2-105 yields:

$$\boxed{w_S = \frac{m\Delta P}{SGPS\rho_W\varepsilon_i}} \tag{2-107}$$

The mass density of water, ρ_W, is:

$$\rho_W = 1{,}000\ \text{kg}/\text{m}^3 \tag{2-108}$$

The mass flow rate through the pump 1 in the Base Case is:

$$m = \frac{1030\text{ton}\times1000\text{kg}/\text{ton}}{3600\text{sec}} = 286\ \text{kg}/\text{sec} \tag{2-109}$$

Experimental tests showed that the specific gravity of the pumped solution, SGPS, for the Base Case was:

$$SGPS = 0.8 \tag{2-110}$$

The differential pump pressure was selected for the Base Case to be:

$$\Delta P = 0.5\ \text{atm} \tag{2-111}$$

From conversion tables in Perry & Chilton (References, 5.11), it is found that:

$$\boxed{1\ \text{atm} = 1.01325\times10^5\ \text{N}/\text{m}^2} \tag{2-112}$$

The intrinsic efficiency of the pump was selected for the Base Case to be (Ulrich p.205, Table 4-20):

$$\varepsilon_i = 0.6 \qquad (2\text{-}113)$$

Inserting $\dot{m}$ from eqn. 2-109, ΔP from eqn. 2-111, SGPS from eqn. 2-110, ρ_W from eqn. 2-108, atm from eqn. 2-112, and ε_i from eqn. 2-113 into eqn. 2-107 yields:

$$w_S = \frac{286\text{kg/sec} \text{x} 0.5 \text{x} 1.01325 \text{x} 10^5 \text{N/m}^2}{0.8 \text{x} 1000 \text{kg/m}^3 \text{x} 0.6} =$$

$$= 30{,}186.4 \text{ (Nm / sec)} = 30.2 \text{ kW} \qquad (2\text{-}114)$$

Ulrich's Fig. 5-49 (p. 310), or Fig. 2-6 in the present report, gives C_p as an empirical functional relationship to $\dot{w}_S$, i.e.:

$$\boxed{C_p = C_p(w_S)} \qquad (2\text{-}105)$$

where:

$C_p(w_S)$ = Centrifugal Pump functional relationship of C_p to w_S

Figure 2-6, for centrifugal pump, and for $\dot{w}_S$ equal to 30 kW, produces:

$$C_p = \$10{,}617 \qquad (2\text{-}116)$$

The insert equation in Ulrich's Fig. 5-49, or Fig.2-6 in the present report, gives:

$$\boxed{C_{BM} = C_p \times F_{BM}} \qquad (2\text{-}117)$$

where:

C_{BM} = Bare Module Cost
F_{BM} = Bare Module Factor

The insert table in Ulrich's Fig. 5-49, for centrifugal pumps constructed of cast steel material gives:

$$F_M = 1.4 \qquad (2\text{-}118)$$

where:

F_M = Construction Material Factor

The above cost was adjusted by Ulrich to take into account the barometric pressure of the fluid through the pump (Ulrich's Fig. 5-50 (p. 310), or Figure 2-7 in the present report). This figure provides a Pressure Factor, F_p, as a function of the suction pressure, p_i, for three different types of pumps: centrifugal, rotary with positive displacement, and reciprocating. For centrifugal pumps:

$$\boxed{F_p = C_p(p_i)} \qquad (2\text{-}119)$$

where:
$C_p(p_i)$ = Centrifugal Pump Functional Relationship of F_p on p_i

The Base Case assumes a barometric pressure inside the bioreactor equal to 1 atm. Fig. 5-50 gives p_i in barg units. By definition, barg is the gage or differential pressure between the pressure inside the vessel and the atmospheric pressure outside it. Therefore, when the inside and outside vessel pressures are both equal to 1 atm, the pump operates at 0 barg. Fig. 5-50 indicates that for all three types of pumps, at p_i values less than 10, no pressure correction is needed, and:

$$F_p = 1.0 \qquad (2\text{-}120)$$

Ulrich provides the Bare Module Factor, F_{BM}, as a function of material and pressure factors for pumps in his Fig. 5-51 (p. 311), or Fig. 2-8 in the present report. This relationship can be expressed as:

$$\boxed{F_{BM} = MPF(F_p \times F_M)} \qquad (2\text{-}121)$$

where:
$MPF(F_p \times F_M)$ = Material and pressure factors functional relationship of bare module factor on material factor and pressure factor for pumps

In the Base Case, according to eqns. 2-118 and 2-120:

$$[F_p \times F_M] = 1.0 \times 1.4 = 1.4 \qquad (2\text{-}122)$$

Fig. 5-51 with $[F_p \times F_M]$ equal to 1.4 indicates that:

$$F_{BM} = 4.05 \qquad (2\text{-}123)$$

Inserting C_p from eqn. 2-116 and F_{BM} from eqn. 2-123 into eqn. 2-117 yields:

$$C_{BM} = \$10,617 \times 4.05 = \$42,999 \tag{2-124}$$

This is a 1982 cost. The 1993 cost is given by eqn. 2-95:

$$C_{BM,1993} = \$42,999 \times 1.1403 = \$49,031 \tag{2-125}$$

2.3.4 Pump No.2

The mass flow rate through pump No. 2 is 770 ton/hr of bacterial aqueous phase (Fig. 2-2). Therefore:

$$m = 770\ \text{ton/hr} = 770,000\ \text{kg}/3600\ \text{sec} = 213.89\ \text{kg/sec} \tag{2-126}$$

It is assumed that the specific gravity of the bacterial aqueous phase is equal to that of pure water. By definition:

$$SG_W = 1.0 \tag{2-127}$$

where:

SG_W = Specific Gravity of Water

Therefore:

$$SGPS = 1.0 \tag{2-128}$$

where:

SGPS = Specific gravity of pumped solution

It is assumed for the Base Case that the pressure drop across Pump No. 2 is 0.5 atm, as was assumed for Pump No. 1 (Table 1-2). Therefore:

$$\Delta P = 0.5\ \text{atm} \tag{2-129}$$

It is assumed that the intrinsic efficiency for Pump No.2 is 0.6, as was assumed for pump No.1 (See Table 1-2). Therefore:

$$\varepsilon_i = 0.6 \tag{2-130}$$

Inserting m from eqn. 2-126, ΔP from eqn. 2-129, E_i from eqn. 2-130, SGPS from eqn. 2-128, ρ_W from eqn. 2-108, and atm from eqn. 2-112 into eqn. 2-107, yields:

$$w_S = \frac{213.89\text{kg/sec} \times 0.5\text{atm} \times 1.01325 \times 10^5 \text{N/m}^2}{1000\text{kg/m}^3 \times 0.6} =$$

$$= 18{,}060.33 \text{ W} = 18.1 \text{ kW} \tag{2-131}$$

Ulrich's Fig. 5-49 (p.310), or Fig. 2-6 in the present report, for centrifuge pumps at a shaft power of 18 kW gives:

$$C_P = \$8{,}649 \tag{2-132}$$

For centrifugal pumps made of cast steel, the insert table in Ulrich's Fig. 5-49 gives:

$$F_M = 1.4 \tag{2-133}$$

Since the pressure inside the bioreactor was assumed for the Base Case to be 1 atm (Table 1-2), as it was explained in Section 2.3.3 - Pump No. 1:

$$F_P = 1.0 \tag{2-134}$$

Therefore:

$$[F_P \times F_M] = 1.0 \times 1.4 = 1.4 \tag{2-135}$$

Ulrich's Fig. 5-51 (p. 311), or Fig. 2-8 in the present report, at $[F_P \times F_M]$ equal to 1.4 gives:

$$F_{BM} = 4.05 \tag{2-136}$$

Inserting C_P from eqn. 2-132 and F_{BM} from eqn. 2-136 into eqn. 2-117 yields:

$$C_{BM,1982} = \$8{,}649 \times 4.05 = \$35{,}028 \tag{2-137}$$

The cost in 1993 dollars is given by eqn. 2-95:

$$C_{BM,1993} = \$35{,}028 \times 1.1403 = \$39{,}943 \tag{2-138}$$

2.3.5 Sedimentation Centrifuge Separator

Inserting the mass density of the pumped solution, ρ, from eqn. 2-106 into eqn. 2-104 yields:

$$\boxed{q=\frac{m}{SGPS\rho_w}} \tag{2-139}$$

Figure 2-1 shows that the mass flow rate through the sedimentation centrifuge is:

$$m = 144\ \text{ton/hr} = 144{,}000\ \text{kg}/3{,}600\ \text{sec} = 40\ \text{kg/sec} \tag{2-140}$$

The specific gravity of the pumped solution into the sedimentation centrifuge is given by:

$$\boxed{SGPS=\frac{m_o}{m_{ps}}\,SGOP+\frac{m_{ap}}{m_{ps}}\,SGAP} \tag{2-141}$$

where:

SGPS = Specific Gravity of Pumped Solution
SGOP = Specific Gravity of Oil Phase
SGAP = Specific Gravity of Aqueous Phase
m_o = Mass Flow Rate of the Oil Phase leaving the sedimentation centrifuge
m_{ps} = Mass Flow Rate of the Pumped Solution entering the sedimentation centrifuge
m_{ap} = Mass Density of Bacterial Aqueous Phase leaving the sedimentation centrifuge

This equation indicates that the specific gravity of the pumped solution is the weighted average of the specific gravities of the two liquid phases making up the solution, the weighing factors being the ratios of the mass flow rates of the two single phases leaving the centrifuge, over the flow rate of the two-phase solution entering it.

Figure 2-1 indicates that:

$$m_o = 83\ \text{ton/hr} \tag{2-142}$$

$$m_{ps} = 144\ \text{ton/hr} \tag{2-143}$$

$$m_{ap} = 61\ \text{ton/hr} \tag{2-144}$$

Figure 2-1 gives for the feed oil the following oil-phase amounts per batch:

$$\text{Oil Phase/batch} = 250{,}000\ \text{gal/batch} = 757\ \text{ton/batch} \qquad (2\text{-}145)$$

Unit conversion tables such as in Perry & Chilton (Reference Section 9.1.1) yield:

$$\boxed{1\ \text{ton} = 1{,}000\ \text{kg}} \qquad (2\text{-}146)$$

where:
ton = metric ton

Inserting gal from eqn. 2-84 and ton from eqn. 2-146 into eqn. 2-145 yields:

$$250{,}000\ \text{gal} \times 3.785411 \times 10^{-3}\ \text{m}^3/\text{gal of oil phase} = \\ = 757\ \text{ton} \times 1{,}000\ \text{kg/ton of oil phase}$$

or,

$$1\ \text{kg of oil phase} = 1.250 \times 10^{-3}\ \text{m}^3\ \text{of oil phase}$$

Therefore, the mass density of oil phase is:

$$\rho_O = 800\ \text{kg/m}^3 \qquad (2\text{-}147)$$

where:
ρ_O = Mass Density of Oil Phase

The specific gravity of a fluid is the ratio of its mass density to the mass density of water. Thus, in the case of the oil phase:

$$\boxed{SGOP = \frac{\rho_O}{\rho_W}} \qquad (2\text{-}148)$$

where:
SGOP = Specific Gravity of Oil Phase

Inserting ρ_W from eqn. 2-108 and ρ_O from eqn. 2-147 into eqn. 2-148 yields:

$$SGOP = [800\text{kg/m}^3]/[1000\text{kg/m}^3] = 0.8 \qquad (2\text{-}149)$$

Eqn. 2-149 confirms the experimental data of eqn. 2-109.

We assumed that the specific gravity of the bacteria aqueous phase is equal to the specific gravity of water, which, by definition, is 1. Therefore:

$$SGAP = 1 \tag{2-150}$$

Inserting m_o from eqn. 2-142, m_{ps} from eqn. 2-143, m_{ap} from eqn. 2-144, SGOP from eqn. 2-149 and SGAP from eqn. 2-150 into eqn. 2-140 yields:

$$SGPS = (83/144) \times 0.8 + (61/144) \times 1 = 0.885 \tag{2-151}$$

Inserting m from eqn. 2-140, SGPS from eqn. 2-151, and ρ_w from eqn. 2-108 into eqn. 2-139 yields:

$$q = 40\ \text{kg/sec} \ / \ [0.885 \times 1{,}000\ \text{kg/m}^3] = 0.045\ \text{m}^3/\text{sec} \tag{2-152}$$

Ulrich's Fig.5-55 (p.313), or Fig.2-9 in the present report, provides:

$$\boxed{C_p = SC(q)} \tag{2-153}$$

where:
C_p = Purchased Equipment Cost
$SC(q)$ = Sedimentation centrifuge functional relationship of purchased equipment cost to volumetric flow rate

For $q = 0.045\ \text{m}^3/\text{sec}$, Ulrich's Fig.5-55 gives:

$$C_p = \$144{,}108 \tag{2-154}$$

The insert table in Ulrich's Fig.5-55, for centrifuges made of carbon steel gives:

$$F_{BM} = 2.0 \tag{2-155}$$

Inserting C_p from eqn. 2-154 and F_{BM} from eqn. 2-155 into eqn. 2-89 yields:

$$C_{BM} = \$144{,}108 \times 2 = \$288{,}216 \tag{2-156}$$

This purchased equipment cost is a 1982 cost; eqn. 2-95 gives:

$$C_{MB,1993} = \$288{,}216 \times 1.1403 = \$328{,}653 \tag{2-157}$$

2.3.6 Precipitation Drum

The precipitation drum consists of two parts, a drum vessel, and an agitator. The methodology for costing of these two parts is shown, separately, below.

2.3.6.1 Vessel

In the Base Case (Table 1-2) the volume of the precipitation drum was chosen to be:

$$V = 50{,}000 \text{ gal} \qquad (2\text{-}158)$$

where:
V = Volume of precipitation drum

Inserting gal from eqn. 2-84 into eqn. 2-158 yields:

$$V = 50{,}000 \text{ gal} \times 3.785411 \times 10^{-3} \text{ m}^3/\text{gal} = 189.27 \text{ m}^3 \qquad (2\text{-}159)$$

Ulrich's curve for Bullet, 0-10 barg, Fig.5-61 (p.316), or Figure 2-3 in the present report, gives C_p as a functional relationship of V through the empirical curve for Bullet, 0-10 barg. It can be denoted:

$$\boxed{C_p = B_{0\text{-}10}(V)} \qquad (2\text{-}160)$$

where:
C_p = Purchased equipment cost
$B_{0\text{-}10}(V)$ = Bullet 0-10 barg functional relationship of C_p to V.

Ulrich's Fig.5-61 at $V = 189.27 \text{ m}^3$ gives:

$$C_p = \$45{,}068 \qquad (2\text{-}161)$$

The insert table in Ulrich's Fig.5-61 for vessels made of carbon steel gives:

$$F_{BM} = 1.9 \qquad (2\text{-}162)$$

Inserting C_p from eqn. 2-161 and F_{BM} from eqn. 2-150 into eqn. 2-89 yields:

$$C_{BM} = \$45{,}068 \times 1.9 = \$85{,}629 \qquad (2\text{-}163)$$

This is a 1982 cost. Inserting $C_{BM,1982}$ from eqn. 2-163 into eqn. 2-96 yields:

$$C_{BM,1993} = \$85{,}629 \times 1.1403 = \$97{,}643 \qquad (2\text{-}164)$$

2.3.6.2 Agitator

The agitator is cost through Ulrich's Fig.5-42 (p.306), or Fig.2-10 in the present report, and Ulrich's Table 4-16 (p.169) or Table 2-1 in the present report. This Table for "Liquid-Liquid, mild" agitators of the axial turbine type, gives:

$$\text{Power (P) Range} = 0.1 \times V^{0.8} - 0.2 \times V^{0.8} \qquad (2\text{-}165)$$

By selecting the upper limit of power:

$$P = 0.2 \times V^{0.8} \qquad (2\text{-}166)$$

Inserting V from eqn. 2-159 into eqn. 2-166 yields:

$$P = 0.2 \times [189.27 \text{ m}^3]^{0.8} = 13.26 \text{ kW} \qquad (2\text{-}167)$$

Ulrich's Fig.5-42, stuffing box curve, provides C_P as an empirical functional relationship to P. This can be denoted as:

$$\boxed{C_P = SB(P)} \qquad (2\text{-}168)$$

where:
C_P = Purchased Equipment Cost
SB(P) = "Stuffing Box" Empirical Functional Relationship of C_P to P

Ulrich's Fig.5-42 at p = 13.26 kW gives:

$$C_P = \$13{,}994 \qquad (2\text{-}169)$$

The insert table in Ulrich's Fig.5-42 for agitators made of Stainless Steel gives:

$$F_{BM} = 2.5 \qquad (2\text{-}170)$$

Inserting C_P from eqn. 2-169 and F_{BM} from eqn. 2-170 into eqn. 2-89 yields:

$$C_{BM} = \$13{,}994 \times 2.5 = \$34{,}985 \qquad (2\text{-}171)$$

This is a 1982 cost. Putting $C_{BM,1982}$ from eqn. 2-171 into eqn. 2-95 yields:

$$C_{BM,1993} = \$34,985 \times 1.1403 = \$39,893 \qquad (2\text{-}172)$$

The overall cost of the precipitation drum is:

$$\boxed{C^{PD}_{BM} = C^{V}_{BM} + C^{A}_{BM}} \qquad (2\text{-}173)$$

where:
C^{PD}_{BM} = Purchased cost (1993) of precipitation drum
C^{V}_{BM} = Purchased cost (1993) of drum vessel
C^{A}_{BM} = Purchased cost (1993) of drum agitator

Inserting C^{V}_{BM} from eqn. 2-164 and C^{A}_{BM} from eqn. 2-172 into eqn. 2-173 yields:

$$C^{PD}_{BM} = \$97,643 + \$39,893 = \$137,536 \qquad (2\text{-}174)$$

2.3.7 Filter Press

The cost of the filter press is estimated through Ulrich's Fig.5-57 (p.314), or Figure 2-11 of the present report.

It was selected that in the Base Case that:

$$A = 10\ m^2 \qquad (2\text{-}175)$$

where:
A = Surface area of the filter press

Ulrich's Fig.5-57, Plate and Frame curve, gives C_p as an empirical functional relationship of A. It can be denoted:

$$\boxed{C_p = PF(A)} \qquad (2\text{-}176)$$

where:
C_p = Purchased equipment cost
PF(A) = Plate and Frame empirical functional relationship of C_p to A.

Ulrich's Fig.5-57 at $A = 10\ m^2$ gives:

$$C_p = \$7,325 \qquad (2\text{-}177)$$

The insert table in Ulrich's Fig.5-57, for polypropylene filters of plate and frame type, gives:

$$F_{BM} = 3.5 \qquad (2\text{-}178)$$

Inserting C_P from eqn. 2-177 and F_{BM} from eqn. 2-178 into eqn. 2-89 yields:

$$C_{BM} = \$7{,}325 \times 3.5 = \$25{,}637 \qquad (2\text{-}179)$$

This is a 1982 cost, i.e. $C_{BM,1982}$. Substituting $C_{BM,1982}$ from eqn. 2-179 into eqn. 2-95 yields:

$$C_{BM,1993} = \$25{,}637 \times 1.1403 = \$29{,}234 \qquad (2\text{-}180)$$

2.3.8 Optional Single-Phase Holding Tank

This is an optional item equipment which was not included in the present study. Thus, the block diagram of Figure 2-2 was cost in the present study, instead of the block diagram of Figure 2-1.

2.3.9 Total BNL Battery Limit Process Equipment (BLE) Costs

1.	Bioreactor (Section 2.3.1)	93,359
2.	Motionless Mixer (Section 2.3.2)	43,862
3.	Pump No.1 (Section 2.3.3)	49,031
4.	Pump No.2 (Section 2.3.4)	39,943
5.	Sedimentation Centrifuge Separator (Section 2.3.5)	328,653
6.	Precipitation Drum (Section 2.3.6)	137,536
7.	Filter Press (Section 2.3.7)	29,234
8.	Single Phase Holding Tank (Section 2.3.8)	--
	Total Product. + Environ. Controls Equip. Cost	$721,618

Thus:

$$\{\text{Total Product. + Envir. Contr. Equip. Cost}\} = \$721{,}618 \qquad (2\text{-}181)$$

Inserting the above equipment cost into eqn. 2-3 yields:

$$BLE = 1.1 \times \$721{,}618 = \$793{,}780 \qquad (2\text{-}182)$$

2.4 Numerical Example of Computing the Net Realization for the Base Case of the BNL's Process

2.4.1 Steam, Oxygen, Boiler Feed Water, Cooling Water

In the Base Case of the BNL process, no steam, oxygen, boiler feed water, or cooling water are consumed. Therefore:

$$ST = 0 \tag{2-183}$$

where:
ST = Cost of steam

$$O_2 = 0 \tag{2-184}$$

where:
O_2 = Cost of oxygen

$$BFW = 0 \tag{2-185}$$

where:
BFW = Cost of boiler feed water

$$CW = 0 \tag{2-186}$$

where:
CW = Cost of cooling water

2.4.2 Electric Energy

The energy consumed in the plant drives the motors of pump No.1, pump No.2, sedimentation centrifuge, and agitator of precipitation drum, plus the energy consumed for lighting, heating, ventilation, and air conditioning (HVAC). Therefore:

$$\boxed{E_T = E_{p1} + E_{p2} + E_{sc} + E_a + E_\ell} \tag{2-187}$$

where:
E_T = Total energy consumed by the motors and the lighting and HVAC systems of the upgrading plant
E_{p1} = Energy consumed by motor of pump No.1
E_{p2} = Energy consumed by motor of pump No.2

E_{sc} = Energy consumed by motor of sedimentation centrifuge
E_a = Energy consumed by motor of agitator of precipitation drum
E_ℓ = Energy consumed for lighting and heating, ventilation, and air conditioning (HVAC)

The energy consumed for lighting and HVAC, E_ℓ, is assumed to be a certain percentage of the energy consumed by all plant motors. Therefore:

$$\boxed{E_\ell = PC_{pm} x [E_{p1} + E_{p2} + E_{sc} + E_a]} \quad (2\text{-}188)$$

where:
PC_{pm} = Percentage of energy consumed by all plant motors representing energy consumed for lighting and HVAC

Inserting E_ℓ from eqn. 2-188 into eqn. 2-187 yields:

$$\boxed{E_p = [E_{p1} + E_{p2} + E_{sc} + E_a] \times (1 + PC_{pm})} \quad (2\text{-}189)$$

It is assumed that the shaft power, w_s, of two motors pumping fluids of similar density through two different vessels is proportional to the relative mass flow rates through them. Thus:

$$\boxed{w_{s,sc} = w_{s,p2} \frac{m_{sc}}{m_{p2}}} \quad (2\text{-}190)$$

where:
$w_{s,sc}$ = Shaft power of sedimentation centrifuge motor
$w_{s,p2}$ = Shaft power of Pump No.2 motor
m_{sc} = Mass flow rate through sedimentation centrifuge
m_{p2} = Mass flow rate through Pump No.2

Eqn. 2-190 implies that the mass density of the fluid entering the sedimentation centrifuge is the same as the mass density of the fluid circulating through Pump No.2. The fluid entering the sedimentation centrifuge is a fully homogenized, one-phase solution of oil and aqueous bacterial solution. On the other hand, the fluid circulating through Pump No.2 at the early cycles through the bioreactor is predominantly, an aqueous bacterial solution. However, close to the last cycles of the biochemical batch process (Figure 2-1), the fluid circulating through this pump has become an almost fully homogenized, single phase oil-aqueous solution, similar to that entering the sedimentation centrifuge. Therefore, the assumption implied in eqn. 2-190 is a reasonable one.

The annual electric energy, E, consumed by a motor is given by:

$$\boxed{E = \frac{w_s}{\eta} HPY} \qquad (2\text{-}191)$$

w_s = Shaft power of motor
HPY = Hours per year of motor operation
η = Electric efficiency of motor

It is assumed that all motors have electric efficiency $\eta = 0.80$.

The annual hours of motor operation are given by:

$$\boxed{HPY = BPY \times HPB} \qquad (2\text{-}192)$$

where:
BPY = Number of process batches per year
HPB = Hours per batch of motor operation

The annual batches of process operation are given by:

$$\boxed{BPY = [SDPY \times 24\ hr/sd]\ /BTPT} \qquad (2\text{-}193)$$

where:
SDPY = Stream days per year
BTPT = Batch Total Processing Time

Table 2-1 indicates that for the Base Case:

$$SDPY = 330\ sd/yr \qquad (2\text{-}194)$$

$$BTPT = 48\ hrs/batch \qquad (2\text{-}195)$$

Putting SDPY from eqn. 2-194 and BTPT from eqn. 2-195 into eqn. 2-193 yields:

$$BPY = [330\ sd/yr \times 24\ hr/sd]\ /\ 48\ hr/batch = 165\ batch/yr \qquad (2\text{-}196)$$

Figure 2-1 shows that 568 ton of bacterial aqueous solution will be recirculated 50 times through the bioreactor by pump No.2, at a mass flow rate of 770 ton/hr. Therefore, the time per batch required for Pump No.2 to remain in operation is:

$$HPB_{p2} = 568 \text{ ton/batch} \times 50 \ / \ 770 \text{ ton/hr} = 36.8 \text{ hr} \qquad (2\text{-}197)$$

Figure 2-1 also indicates that 757 ton of oil phase will be recirculated 50 times through the bioreactor by pump No.1, at a mass flow rate of 1030 ton/hr. Therefore, the time per batch required for Pump No.1 to remain in operation is:

$$HPB_{p1} = [757 \text{ ton/batch}] \times 50 \ / \ 1030 \text{ ton/hr} = 36.8 \text{ hr/batch} \qquad (2\text{-}198)$$

Inserting BPY from eqn. 2-196 and HPB_{p1} from eqn. 2-198 into eqn. 2-192 yields:

$$HPY_{p1} = [165 \text{ batch/yr}] \times [36.8 \text{ hr/batch}] = 6{,}072 \text{ hr/yr} \qquad (2\text{-}199)$$

Similarly inserting BPY from eqn. 2-196 and HPB_{p2} from eqn. 2-197 into eqn. 2-192 yields:

$$HPY_{p2} = 6{,}072 \text{ hr/yr} \qquad (2\text{-}200)$$

Inserting $w_{s,p1}$ from eqn. 2-114 and HPY_{p1} from eqn. 2-199 into eqn. 2-191 yields:

$$E_{p1} = \frac{30.2 \text{kW} \times 6{,}072 \text{hr/yr}}{0.80} = 229{,}218 \text{ kWh/yr} \qquad (2\text{-}201)$$

Similarly inserting $w_{s,p2}$ from eqn. 2-131 and HPY_{p2} from eqn. 2-200 into eqn. 2-191 yields:

$$E_{p2} = \frac{18.1 \text{kW} \times 6{,}072 \text{hr/yr}}{0.80} = 137{,}379 \text{ kWh/yr} \qquad (2\text{-}202)$$

Figure 2-1 indicates that:

$$m_{sc} = 144 \text{ ton/hr} \qquad (2\text{-}203)$$

$$m_{p2} = 770 \text{ ton/hr} \qquad (2\text{-}204)$$

Inserting $w_{s,p2}$ from eqn. 2-131, m_{sc} from eqn. 2-203 and m_{p2} from eqn. 2-204 into eqn. 2-190 yields:

$$w_{s,sc} = 18.1\ \text{kW} \times [144\ /\ 770] = 3.38\ \text{kW} \qquad (2\text{-}205)$$

The motor pumping the single phase homogeneous oil-bacterial solution into the sedimentation centrifuge moves 568 ton/batch of bacterial aqueous solution plus 757 ton/batch of oil phase into the centrifuge at a mass flow rate of 144ton/hr. Therefore, the time per batch that the sedimentation centrifuge motor must be in operation is:

$$HPB_{sc} = (568 + 757)\ \text{ton/batch}\ /\ 144\ \text{ton/hr} = 9.2\ \text{hr/batch} \qquad (2\text{-}206)$$

Inserting BPY from eqn. 2-196 and HPB_{sc} from eqn. 2-206 into eqn. 2-192 yields:

$$HPY_{sc} = 165\ \text{batch/yr} \times 9.2\ \text{hr/batch} = 1{,}518\ \text{hr/yr} \qquad (2\text{-}207)$$

Inserting $w_{s,sc}$ from eqn. 2-205 and HPY_{sc} from eqn. 2-207 into eqn. 2-191 yields:

$$E_{sc} = \frac{3.38\text{kW} \times 1{,}518\text{hr/yr}}{0.80} = 6{,}414\ \text{kWh/yr} \qquad (2\text{-}208)$$

Figure 2-1 shows that 568 ton/batch of bacterial aqueous solution enter the drum at a mass flow rate of 62.5 ton/hr. Therefore, the amount of time taken for the bacterial solution to pass through the precipitation drum is:

$$HPB_a = \frac{568\text{ton}}{62.5\text{ton/hr}} = 9.1\ \text{hrs} \qquad (2\text{-}209)$$

Inserting BPY from eqn. 2-196 and HPB_a from eqn. 2-209 into eqn. 2-192 yields:

$$HPY_a = 165\ \text{batch/yr} \times 9.1\ \text{hr/batch} = 1{,}502\ \text{hr/yr} \qquad (2\text{-}210)$$

Inserting $w_{s,a}$ from eqn. 2-167 and HPY_a from eqn. 2-210 into eqn. 2-191 yields:

$$E_a = \frac{13.26\text{kW} \times 1{,}502\text{hr/yr}}{0.80} = 24{,}895\ \text{kWh/yr} \qquad (2\text{-}211)$$

The lighting and HVAC annual energy consumption is assumed to be 3% of the total energy consumed annually by all motors in the plant. Therefore:

$$PC_{pm} = 0.03 \qquad (2\text{-}212)$$

Inserting E_{p1} from eqn. 2-201, E_{p2} from eqn. 2-202, E_{sc} from eqn. 2-208, E_a from eqn. 2-211, and PC_{pm} from eqn. 2-212 into eqn. 2-189 yields:

$$\begin{aligned} E_T &= [229{,}218 + 137{,}379 + 6{,}414 + 24{,}895] \times (1 + 0.03) = \\ &= 409{,}843 \text{ kWh/yr} \end{aligned} \qquad (2\text{-}213)$$

The annual cost of energy, PW, is equal to the total energy consumed, E_T, multiplied by the unit cost of energy, PW_u, given by eqn. 2-26 at 0.05 \$/kWh.

$$\boxed{PW = E_T \times PW_u} \qquad (2\text{-}214)$$

Therefore:

$$PW = 409{,}843 \text{ kWh/yr} \times 0.05 \text{ \$/kWh} = \$20{,}492 \qquad (2\text{-}215)$$

2.4.3 Total Utilities Cost

Inserting ST from eqn. 2-183, O_2 from eqn. 2-184, BFW from eqn. 2-185, CW from eqn. 2-186, and PW from eqn. 2-215 into eqn. 2-25 yields:

$$UT = 20{,}492 \text{ \$/yr} \qquad (2\text{-}216)$$

2.4.4 Off-Site And General Facilities (GF), Total Facilities Costs (TFC), Engineering & Home Office Expenses (E&HO), Plant Start-Up And Minor Revamps (PSU), Paid-Up Process Royalties (PR)

Inserting BLE from eqn. 2-182 into eqn. 2-4 yields:

$$GF = 0.35 \times \$793{,}780 = \$277{,}823 \qquad (2\text{-}217)$$

Inserting BLE from eqn. 2-182, UT from eqn. 2-218, and GF from eqn. 2-217 into eqn. 2-2 yields:

$$TFC = 793{,}780 + 20{,}492 + 277{,}823 = \$1{,}092{,}095 \qquad (2\text{-}218)$$

Inserting TFC from eqn. 2-218 into eqn. 2-5 yields:

$$E\&HO = 0.10 \times 1{,}092{,}095 = \$109{,}210 \qquad (2\text{-}219)$$

Inserting TFC from eqn. 2-218 into eqn. 2-6 yields:

$$PSU = 0.05 \times 1{,}092{,}095 = \$54{,}605 \qquad (2\text{-}220)$$

Inserting TFC from eqn. 2-218 into eqn. 2-7 yields:

$$PR = 0.02 \times 1{,}092{,}095 = \$21{,}842 \qquad (2\text{-}221)$$

2.4.5 Annual Feed (FEEDA), Fuel Gas (FG), Catalyst (CAT), Labor (LB), Maintenance (MT), Overheads, Property Taxes, Insurance, Capital Charges (CC), Operating Costs (OC)

In the Base Case, we use as feed High Sulfur Resid Fuel Oil with 3.0% S delivered at N.Y. Harbor. We quote the prices reported in the Tuesday, September 14, 1993 issue of Platt's Oilgram Price Report, in the table "Five-Day Rolling Averages," the portion of which on Low and High Sulfur Resid Fuel Oil is shown in the present report (Table 2-2).. The prices for three Low Sulfur Resid Fuel Oil grades (0.3%, 0.7% and 1%), and for two Hi Sulfur Resid Fuel Oil grades (2.2% and 3%) are given. These five data points are fitted with a linear price curve derived by the least squares deviation method (Appendix A). The resulting curve is shown in Figure 2-12; its analytic representation is:

$$\boxed{C = A + B \times S} \qquad (2\text{-}222)$$

where:

C = Cost of NY cargo resid fuel oil per barrel

$$A = 16.646 \qquad (2\text{-}223)$$

$$B = -2.024 \qquad (2\text{-}224)$$

This curve gives a price for 3% Sulfur equal to:

$$C = 16.646 - 2.024 \times 3 = 10.574\ \$/\text{bbl} \qquad (2\text{-}225)$$

Thus, the cost of daily feed is:

$$FEEDD = [250{,}000\ \text{gal} / (2\ \text{days} \times 42\ \text{gal}/\text{bbl})] \times 10.574\ \$/\text{bbl} = 31{,}470\ \$/\text{day} \qquad (2\text{-}226)$$

Inserting TFC from eqn. 2-218, and FEEDD from eqn. 2-226 into eqn. 2-8 yields:

$$WC = 0.01 \times 1{,}092{,}095 + 20 \times 31{,}470 = \$640{,}321 \qquad (2\text{-}227)$$

Inserting TFC from eqn. 2-218, E&HO from eqn. 2-219, PSU from eqn. 2-220, PR from eqn. 2-221 and WC from eqn. 2-227 into eqn. 2-1 yields:

$$\begin{aligned} TCIC &= 1{,}092{,}095 + 109{,}210 + 54{,}605 + 21{,}842 + 640{,}321 = \\ &= \$1{,}918{,}073 \end{aligned} \qquad (2\text{-}228)$$

The annual feed is the product of the daily feed times the number of operating days per year. Thus:

$$\boxed{FEEDA = SDPY \times FEEDD} \qquad (2\text{-}229)$$

where:
SDPY = Stream Days Per Year
FEEDD = Daily Feed
FEEDA = Annual Feed

Inserting FEEDD from eqn. 2-226 and SDPY from eqn. 2-194 into eqn. 2-229 yields:

$$FEEDA = 330 \times 31{,}470 = 10{,}385{,}100\ \$/yr \qquad (2\text{-}230)$$

The BNL plant does not use fuel gas for its utility requirements. Therefore:

$$FG = 0 \qquad (2\text{-}231)$$

where:
FG = Fuel Gas Purchased Cost

The cost of catalyst for the BNL process is the same as the cost of the bacterial culture. Figure 2-1 indicates that for the Base Case the amount of bacterial culture per batch is 150,000 gallons. Table 1-2 shows that, for the Base Case, there are 330 stream days per year, the batch processing time is two days, and the cost of catalyst is 10$/m^3. Therefore, the cost of bacterial culture (or Catalyst) per year is:

$$\begin{aligned} CAT = 10\ \$/m^3 \times [150{,}000\ gal/2\ sd] \times 330\ sd/yr \times \\ 3.785411 \times 10^{-3}\ m^3/gal = 936{,}890\ \$/yr \end{aligned} \qquad (2\text{-}232)$$

where:
CAT = Annual Cost of Catalyst (or Bacterial Culture)

Table 1-2 indicates that there are two Plant Operator-Year labor requirements for the BNL plant. Therefore, according to eqn. 2-40, the annual labor cost is:

$$\begin{aligned} LB &= 280{,}670\ \$/\{\text{Plant Operator-Year}\} \times 2\ \{\text{Plant Operator-Year}\} = \\ &= 561{,}340\ \$/\text{yr} \end{aligned} \tag{2-233}$$

where:
LB = Annual Labor Cost

Inserting TCIC from eqn. 230 into eqn. 2-42 yields:

$$MT = 0.02 \times 1{,}918{,}073 = 38{,}361\ \$/\text{yr} \tag{2-234}$$

where:
MT = Annual Cost of Maintenance

Inserting TCIC from eqn. 2-228, WC from eqn. 2-227, and PR from eqn. 2-221 into eqn. 2-43 yields:

$$\begin{aligned} [OH + PT + IN] &= 0.04 \times \{1{,}918{,}073 - 640{,}321 - 21{,}842\} = \\ &= 50{,}236\ \$/\text{yr} \end{aligned} \tag{2-235}$$

where:
OH = Annual Overhead Cost
PT = Annual Property Taxes
IN = Annual Insurance

Inserting TCIC from eqn. 2-228 into eqn. 2-44 yields:

$$CC = 0.2 \times 1{,}918{,}073 = \$383{,}615 \tag{2-236}$$

where:
CC = Annual Capital Charges

Inserting FEEDA from eqn. 2-230, FG from eqn. 2-231, UT from eqn. 2-218, CAT from eqn. 2-232, LB from eqn. 2-233, MT from eqn. 2-234, [OH + PT + IN] from eqn. 2-235 into eqn. 2-9 yields:

$$OC = 10{,}385{,}100 + 0 + 20{,}492 + 936{,}890 + 561{,}340 + + 38{,}361 + 50{,}236 + 383{,}615 = 12{,}376{,}034 \text{ \$/yr} \quad (2\text{-}237)$$

where:
OC = Annual Operating Cost

Figures 2-13 to 2-19 show the prices of a variety of feeds from different sources and delivered in several locations. The data is obtained from Platt's Oilgram and Bloomberg Oil Buyer's Guide. These data are fit to a linear function of the type C = A + B*S. These coefficients are used in Section 4 for some sensitivity analyses.

2.4.6 Oil Product Credit (OPC), By-Product Credit (BPC), Total Credit (CR), Net Realization (NR)

The annual amount of fuel oil produced by the BNL plant is

$$PRODO = \{[250{,}000 \text{ gal/2sd}] \times 330 \text{ sd/yr}\} / 42 \text{ gal/bbl} = = 982{,}143 \text{ bbl/yr} \quad (2\text{-}238)$$

where:
PRODO = Annual Amount of Product Oil

In the Base Case (Table 1-2), this product oil contains 33% less sulfur than the feed oil. Therefore, the sulfur content in the product oil is:

$$SPROD = 3 \times 0.666 = 2.00 \text{ wt\% S} \quad (2\text{-}239)$$

where:
SPROD = Sulfur Weight Content in the Product Oil

Figure 2-12 indicates that the sale price of product Resid Fuel Oil containing 2.00 wt% sulfur is:

$$C = 16.646 - 2.024 \times 2.00 = 12.598 \text{ \$/bbl} \quad (2\text{-}240)$$

where:
C = Cost of Resid Fuel Oil

The credit from the sale of the product oil is given by:

$$\boxed{OPC = C \times PRODO} \quad (2\text{-}241)$$

where:

OPC = Oil Product Credit

Inserting C from eqn. 2-240 and PRODO from eqn. 2-238 into eqn. 2-241 yields:

$$OPC = 12.598\ \$/bbl \times 982{,}143\ bbl/yr = 12{,}373{,}038\ \$/yr \tag{2-242}$$

It is assumed that the product sulfur is in elemental form, ready for sale without any further processing. This is not an accurate assumption; the processing costs of product sulfur are not known at present, although are anticipated to be minimal. The amount of product sulfur is:

$$\boxed{PRODS = SREM \times PRODOT} \tag{2-243}$$

where:
PRODS = Annual amount of product sulfur
SREM = Weight percent of product oil equal to amount of product sulfur removed
PRODOT = Annual amount of product oil in metric tons

Table 2-1 indicates that for the Base Case:

$$SREM = 0.33 \times 3 = 1\ wt\%\ S \tag{2-244}$$

and

$$PRODOT = (757\ ton / 2sd) \times 330\ sd/yr = 124{,}905\ ton/yr \tag{2-245}$$

Inserting SREM from eqn. 2-244 and PRODOT from eqn. 2-245 into eqn. 2-243 yields:

$$PRODS = 0.01\ X\ 124{,}905\ ton/yr = 1{,}249\ ton/yr \tag{2-246}$$

Conversion unit tables such as in Perry & Chilton (References, Section 9.1.1) give:

$$\boxed{1\ lt = 1.016\ ton} \tag{2-247}$$

where lt represents a long ton.

Inserting ton from eqn. 2-247 into eqn. 2-246 yields:

$$PRODS = 1{,}249 / 1.016 = 1{,}229\ lt/yr \tag{2-248}$$

The revenue from the sale of elemental sulfur by-product is:

$$\boxed{BPC = S_u \times PRODS} \qquad (2\text{-}249)$$

where:
BPC = By-Product Credit
S_u = Selling price of by-product sulfur per long ton

Inserting PRODS from eqn. 2-248 and S from eqn. 2-47 into eqn. 2-249 yields:

$$BPC = 50\ \$/lt \times 1{,}229\ lt/yr = 61{,}450\ \$/yr \qquad (2\text{-}250)$$

Inserting OPC from eqn. 2-242 and BPC from eqn. 2-250 into eqn. 2-61 yields:

$$CR = 12{,}373{,}038 + 61{,}450 = 12{,}434{,}488\ \$/yr \qquad (2\text{-}251)$$

where:
CR = Total Credits of the BNL process

Inserting CR from eqn. 2-251 and OC from eqn. 2-237 into eqn. 2-62 yields:

$$NR = 12{,}434{,}488 - 12{,}376{,}034 = 58{,}454\ \$/yr \qquad (2\text{-}252)$$

where:
NR = Annual Net Realization of BNL process.

The net realization per processed (or product) barrel is:

$$\boxed{NRB = NR/PRODO} \qquad (2\text{-}253)$$

where:
NRB = Net Realization per Processed (or Product) Barrel

Inserting NR from eqn. 2-252 and PRODO from eqn. 2-238 into eqn. 2-253 yields:

$$NRB = [58{,}454\ \$/yr] \ / \ [982{,}143\ bbl/yr] = 0.0595 \sim 0.06\ \$/bbl \qquad (2\text{-}254)$$

Table 2-1 Ulrich's Table 4-16: Criteria and Data for the Preliminary Design of Agitators and Mixers.

	Type of Mixer					*Type of Mixer*										
	Fluid-Agitated					*Mechanically Agitated*										
							Turbine									
	Fluid Jet	*Orifice Plate (pipeline)*	*Motionless Mixer*	*Gas Sparger*	*Pump or Agitated-Line Mixer*	*Propeller*	*Axial*	*Radial*	*Kneader*	*Extruder*	*Roll*	*Muller*	*Single- and Twin-Rotor (porcupine)*	*Hammer Cage, and Attrition Mills*	*Ribbon*	*Drum, Vibratory, Pebble, and Jet Mills*
Range of Equipment Sizes																
Vessel diameter, D_t (m)	30 D_a	0.005–0.5	0.003–2.0	0.01–5	0.01–0.5	<50	<20									
Vessel length or height, L (m)	100 D_a	50 D_t	0.03–80	0.03–5	0.3–2	<20	<40									
Agitator diameter, D_a (m)	0.001–0.1	$0.2D_t$–$0.5D_t$			0.05–0.5	<1.5	<5									
Vessel volume, V(m^3)						<40,000	<1200									
Mixed Fluid Flow Rate, $\dot{m}$ (kg/s)																
Gases	0.001–100	0.03–300	0.001–100	—[e]												
Liquids	0.1–10,000	0.16–16	0.01–1000		0.1–400											
Typical Residence Time, θ (s)																
Mixing	0.1–200	0.16–16	0.02–5.0	—[e]	0.15–1[b]	$12{,}000\,(\mu V/P)^{1/2}\,V^{0.2}$			20–200	20–200	2–10	100–200	20–200	—[c]	20–200	—[c]
Liquid–Liquid extraction						60–20,000	60–1000									
Solids leaching						60	60									
Chemical reaction						From Kinetic Analysis										
Viscosity range (Pa · s)	0.0–0.01	0–0.1	0–1000	0–1.0	0–1.0	0–5	0–500		200–2000	200–10,000	500–2000	500–5000	100–1000	—[c]		
Volume fraction of dispersed medium, φ	<0.4	<0.4		<0.1	<0.8	<0.8	<0.8									
Suitability																
Gas-gas mixing	A	A	A	X	D	E	E	E	X	X	X	X	X	X	X	X
Gas–Liqud mixing	E	D	B	A	B	D	D	A	X	X	X	X	X	X	X	X
Liquid–liquid mixing (miscible)	A	A	A	B	A	B	A	B	X	X	X	X	X	X	X	X
Liquid–liquid dispersion (immiscible)	B	B	D	D	B	B	A	B	X	X	X	X	X	X	X	X
Liquid–solid suspension	B	B	B	D	E	B	A	B	X	X	X	X	X	X	X	X
Paste–paste mixing	X	X	A	X	X	X	C	X	A	A	D	A	B	D	E	E
Solid–solid mixing	X	X	D	—[d]	X	X	X	X	X	X	X	D	B	B	A	A
Heat-transfer enhancement	A	B	D	B	D	B	A	B	B	A	D	D	A	E	C	B
Chemical reaction	A	B	D	A	B	B	A	B	B	B	E	E	A	E	D	B
Liquid-solid mixing	D	D	D	B	D	B	A	B	A	D	B	B	A	B	D	D
Mixing of sticky materials	E	E	A	X	D	E	D	B	B	A	E	E	D	B	E	E
Pressure Differential, Δp (bar)																
Gases	0.3–1.0	0.0002–0.001	8×10^{-6}	—[e]												
Liquids	1–3	0.05–0.3	0.008–0.8	—[e]												
Power Consumption, P (kW)[f]																
Gas–Gas	$1.5\dot{m}$–$5\dot{m}$	$0.03\dot{m}$–$0.15\dot{m}$	$0.001\dot{m}$		$0.15\dot{m}$–$1.5\dot{m}$											
Gas–Liquid		$0.007\dot{m}$–$0.04\dot{m}$	$0.001\dot{m}$	—[e]	$0.04\dot{m}$	1.0V–3.0V		1.0V–2.0V								
Liquid–Liquid																
Mild	$0.007\dot{m}$	$0.007\dot{m}$	$0.001\dot{m}$	—[e]	$0.007\dot{m}$	0.17V–0.3V	$0.1V^{0.8}$–$0.2V^{0.8}$									
Vigorous	$0.01\dot{m}$	$0.02\dot{m}$			$0.02\dot{m}$	0.7V–1.0V	$0.4V^{0.8}$–$0.8V^{0.8}$									
Intense	$0.02\dot{m}$	$0.04\dot{m}$			$0.04\dot{m}$	1.0V–3.0V	$0.8V^{0.8}$–$2.0V^{0.8}$									
Liquid–Solid	$0.007\dot{m}$–$0.02\dot{m}$	$0.007\dot{m}$–$0.04\dot{m}$	$0.001\dot{m}$–$0.1\dot{m}$	—[e]	$0.007\dot{m}$–$0.04\dot{m}$	1.0V–3.0V	$0.8V^{0.8}$–$2.0V^{0.8}$							—[c]		
Paste–Paste			$0.1\dot{m}$						See Figure 4-27				$1\dot{m}$–$5\dot{m}$	—[c]	$1\dot{m}$–$6\dot{m}$	—[c]
Solid–Solid																
Typical overall heat transfer coefficients, U (J/s · m^2 · K)						See Table 4-15			50–500	50–500			20–300[g]			

KEY—A excellent or no limitations, B modest limitations, C special units available at higher cost to minimize problems, D limited in this regard, E severely limited in this regard, X unacceptable

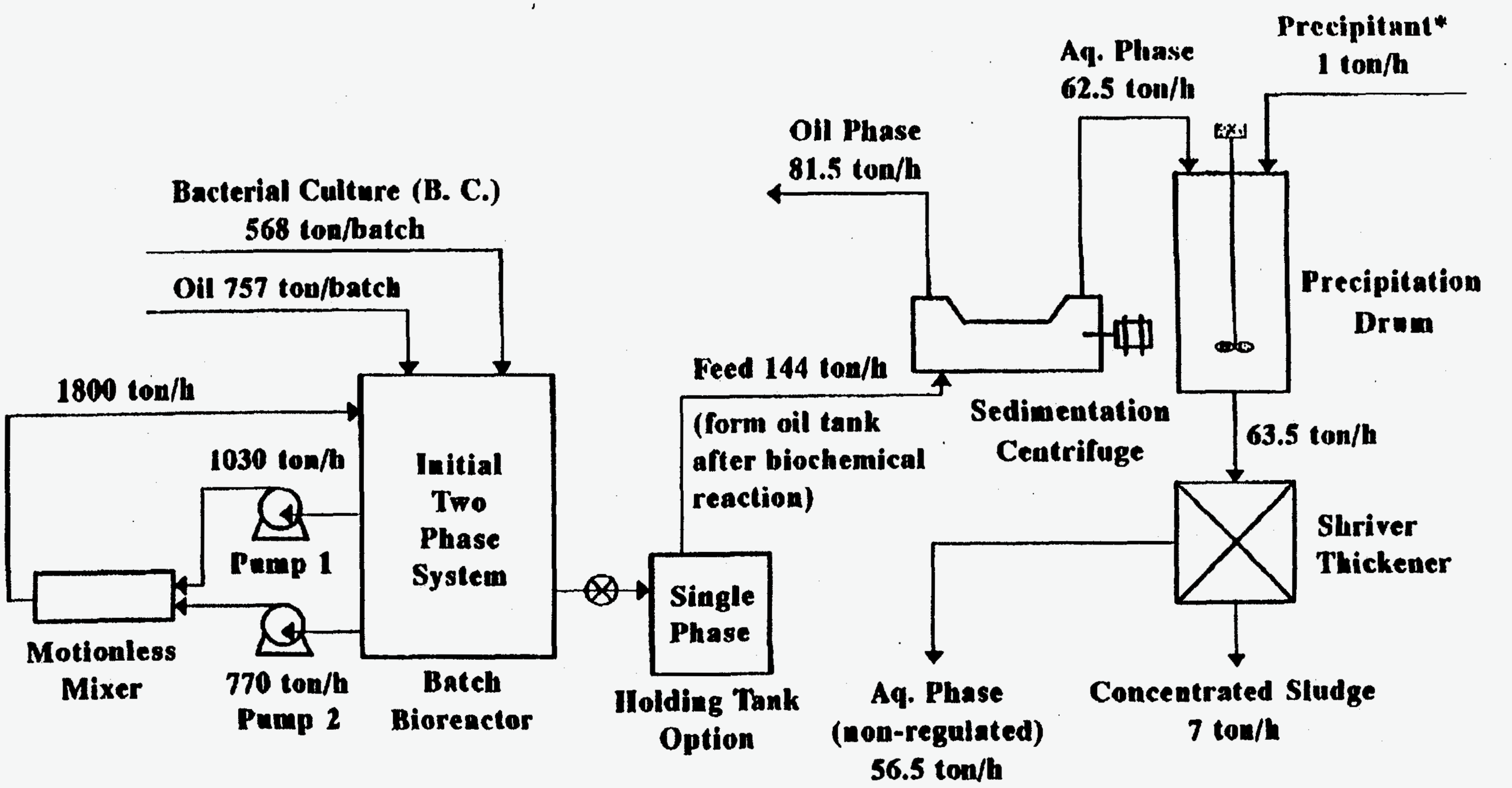
[a] Gas fluxes typically range from 0.004 to 0.06 m^3 per square meter of vessel cross section. Bubble rise velocities normally fall between 0.15 and 0.30 m/s. For detailed design procedures, see J. N. Tilton and T. W. F. Tussell, "Designing Gas-Sparged Vessels for Mass Transfer," *Chemical Engineering*, pp. 61–68 (November 29, 1982). [b] This is residence time within the pump or line mixer itself. For a pump installed in an external pipe loop, the time required for circulating a volume equal to the tank contents is considered to be adequate for mixing of vessel contents. [c] See Table 4-5. [d] See fluid beds. [e] Power consumption can be calculated for a sparger from $P = m_g \epsilon_0 \Delta p / \rho_g$, where m_g is the gas flow rate, ρ_g is the density, ϵ_0 compressor overall efficiency, and Δp the compressor differential pressure. To determine the latter, assume 0.1 to 0.3 bar for pressure drop through the sparger and add the static pressure exerted by the fluid in the vessel. [f] All values include efficiency losses in drive and gears and correspond to the direct electricity or utility consumption. [g] V. W. Uhl and W. L. Root, "Heat Transfer to Granular Solids in Agitated Units," *Chem. Eng. Prog.* 63, pp. 81–92 (1967).

Table 2-2 Platt's Prices for Resid Fuel Oil (Five-Day Rolling Averages, September 14, 1993)

New York Cargo

Percentage of Sulfur	Range ($/BBL)	Average ($/BBL)
.3	16.00 - 16.25	16.125
.7 max	15.00 - 15.25	15.125
1.0	14.60 - 14.85	14.725
2.2	11.69 - 11.94	11.815
3.0	10.69 - 10.94	10.815

Figure 2-1 Block Diagram of the BNL Process for Biochemical Upgrading (Desulfurization) of Heavy Crudes (Optional Single Phase Holding Tank is Included)



1. Biochemical batch process.

(36 hours, 50 cycles)

2. Product and waste processing plant.

(9.2 hours)

Figure 2-2 Alternative Block Diagram of the BNL Biochemical Upgrading Process (Optional Single Phase Holding Tank is not Included)

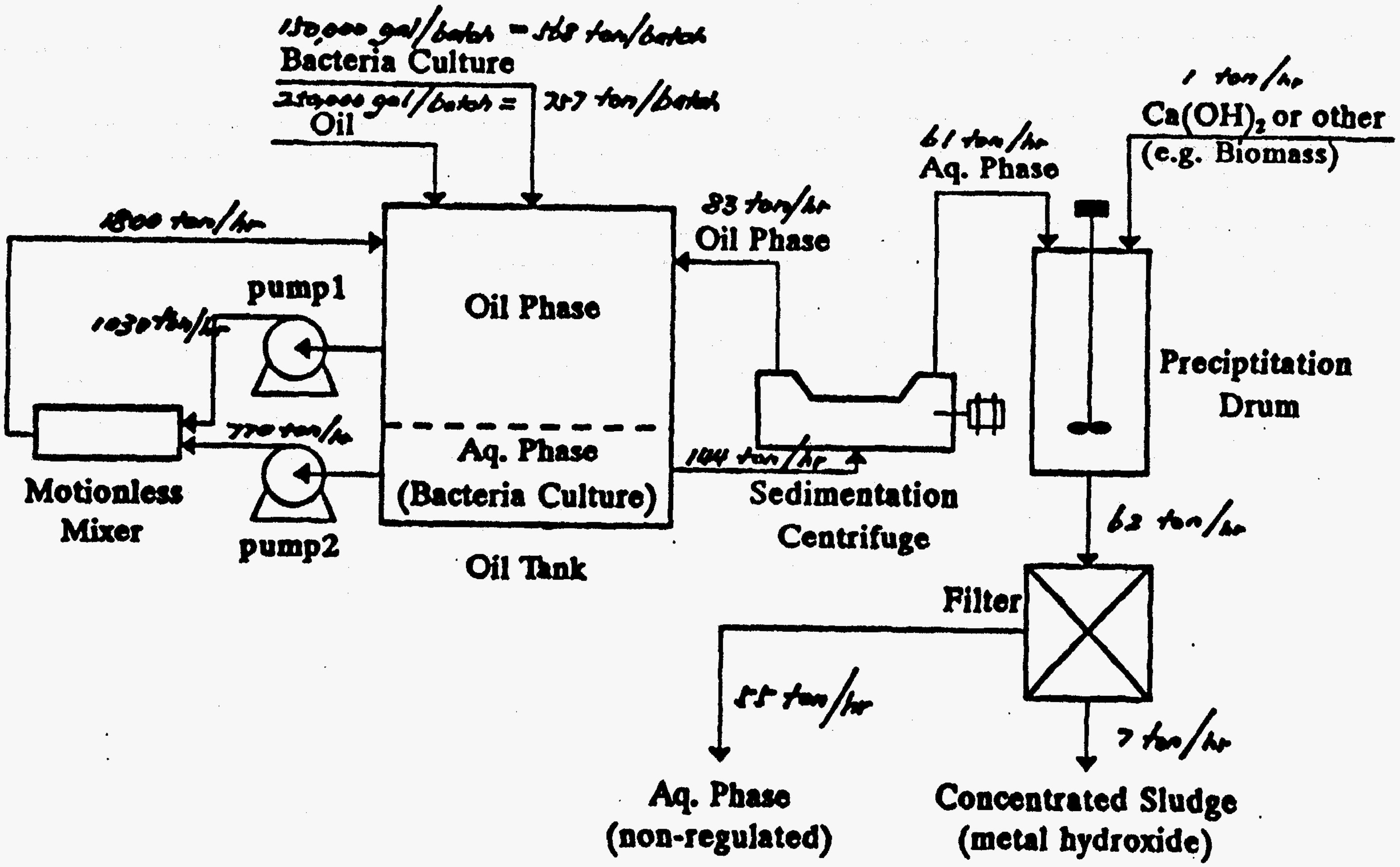
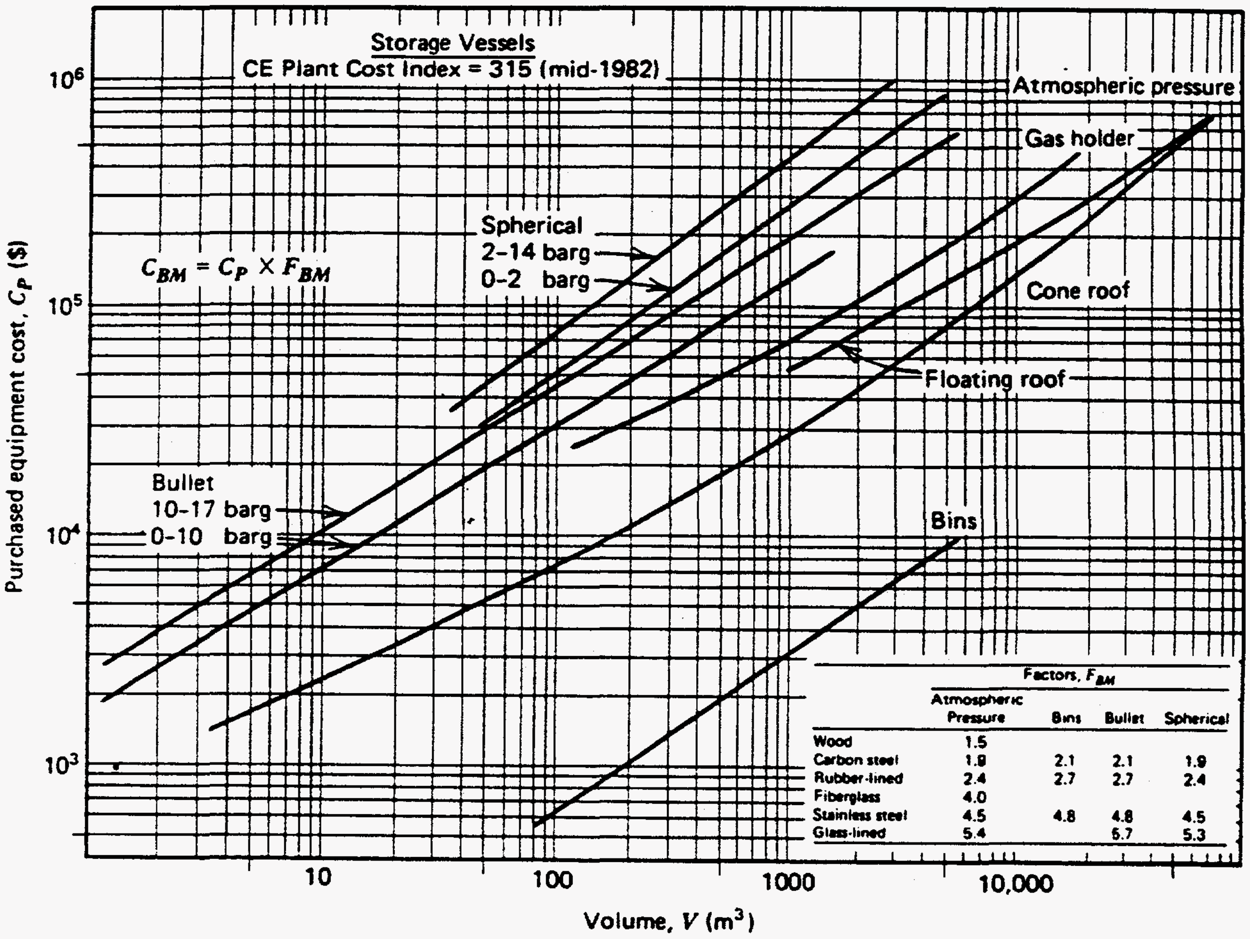
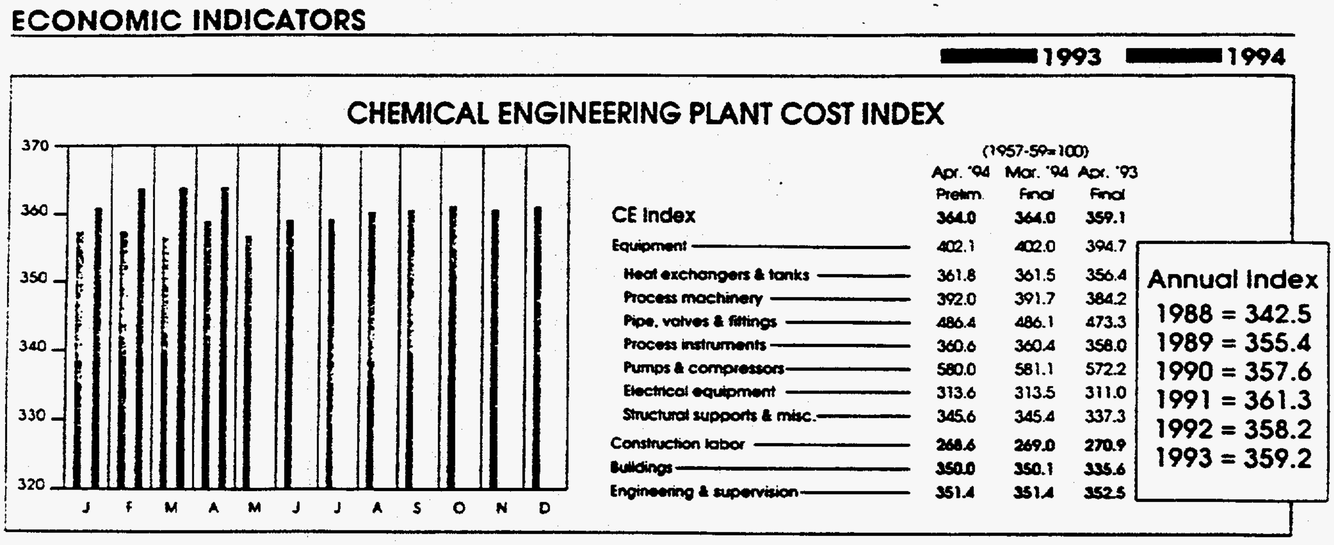


Figure 2-3 Ulrich's Fig. 5-61: Purchased Equipment Costs for Storage Vessels



	Factors, F_{BM}			
	Atmospheric Pressure	Bins	Bullet	Spherical
Wood	1.5			
Carbon steel	1.8	2.1	2.1	1.9
Rubber-lined	2.4	2.7	2.7	2.4
Fiberglass	4.0			
Stainless steel	4.5	4.8	4.8	4.5
Glass-lined	5.4		6.7	5.3

Figure 2-4 Chemical Engineering (CE) Plant Cost Index for 1993-1994



CHEMICAL ENGINEERING PLANT COST INDEX

(1957-59=100)	Apr. '94 Prelim.	Mar. '94 Final	Apr. '93 Final
CE Index	**364.0**	**364.0**	**359.1**
Equipment	402.1	402.0	394.7
Heat exchangers & tanks	361.8	361.5	356.4
Process machinery	392.0	391.7	384.2
Pipe, valves & fittings	486.4	486.1	473.3
Process instruments	360.6	360.4	358.0
Pumps & compressors	580.0	581.1	572.2
Electrical equipment	313.6	313.5	311.0
Structural supports & misc.	345.6	345.4	337.3
Construction labor	268.6	269.0	270.9
Buildings	350.0	350.1	335.6
Engineering & supervision	351.4	351.4	352.5

Annual Index

1988 = 342.5
1989 = 355.4
1990 = 357.6
1991 = 361.3
1992 = 358.2
1993 = 359.2

Figure 2-5 Ulrich's Fig. 5-41: Purchased Equipment Costs for Motionless Mixers

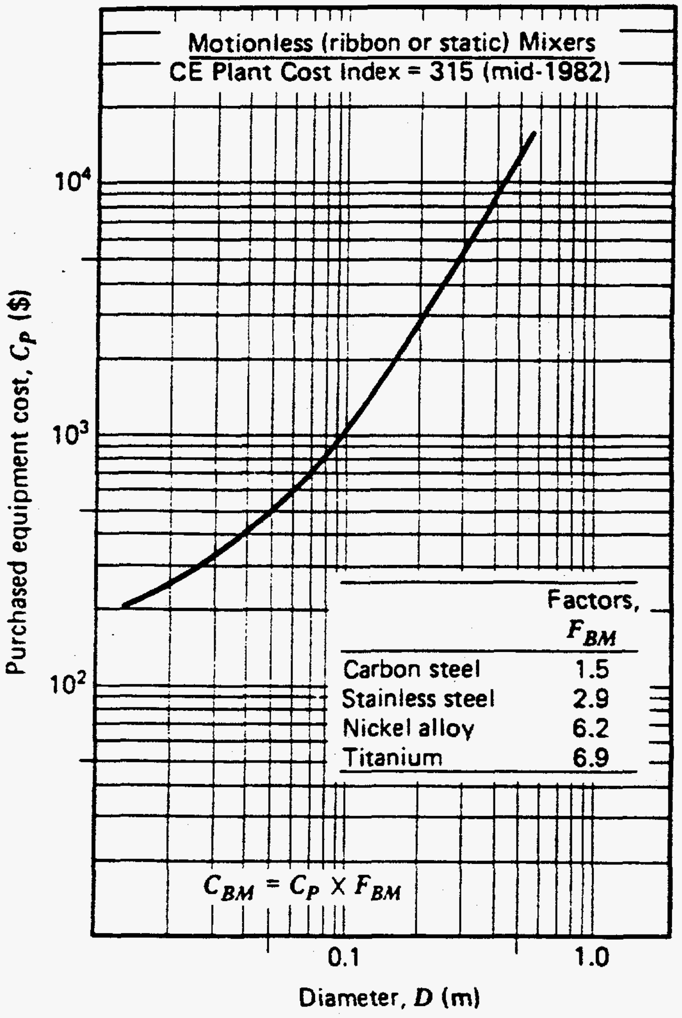
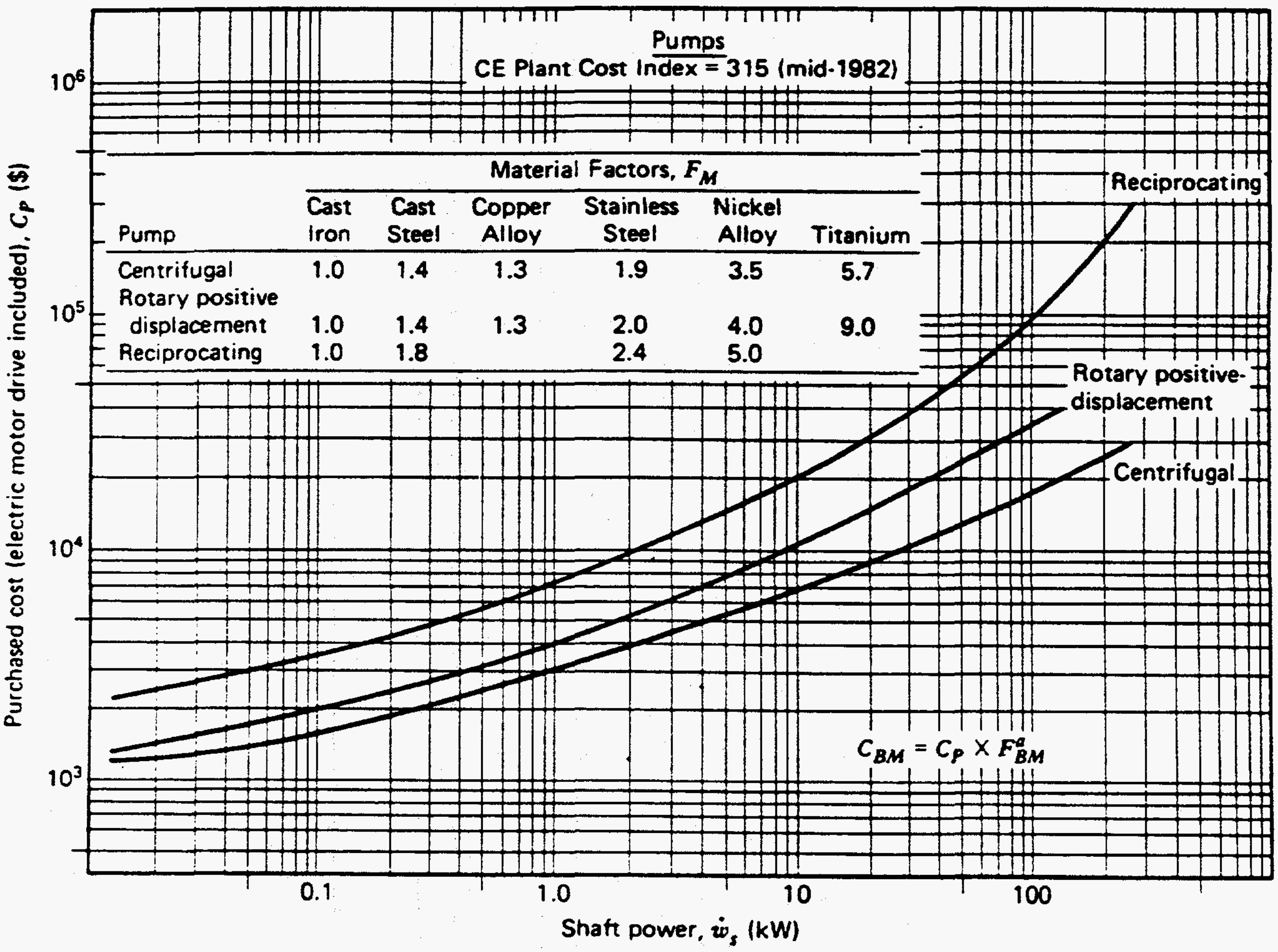


Figure 2-6 Ulrich's Fig. 5-49: Purchased Equipment Costs for Pumps



	Material Factors, F_M					
Pump	Cast Iron	Cast Steel	Copper Alloy	Stainless Steel	Nickel Alloy	Titanium
Centrifugal	1.0	1.4	1.3	1.9	3.5	5.7
Rotary positive displacement	1.0	1.4	1.3	2.0	4.0	9.0
Reciprocating	1.0	1.8		2.4	5.0	

Figure 2-7 Ulrich's Fig. 5-50: Pump Pressure Factor (Ratio of High Purchase Price of High Pump to That of One Designed for 10 barg)

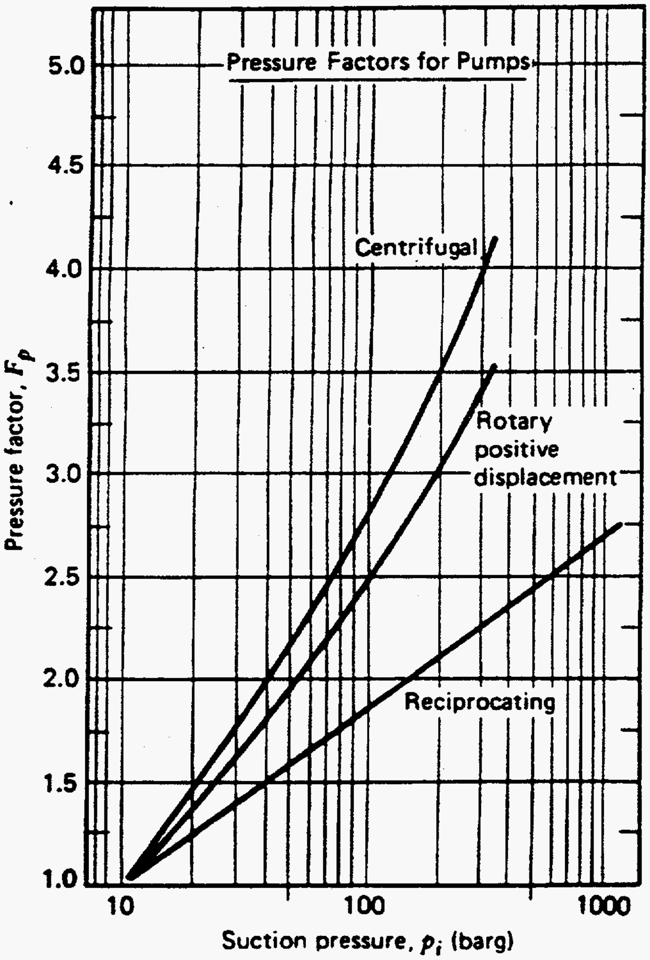


Figure 2-8 Ulrich's Fig. 5-51: Bare Module Factors as a Function of Material and Pressure Factors for Pumps

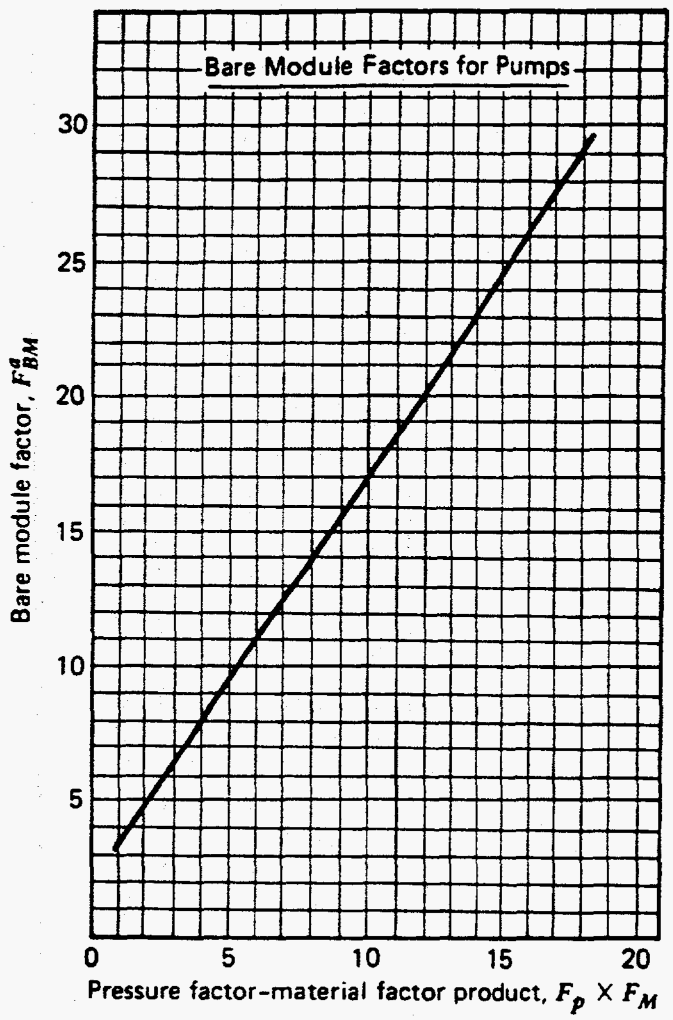
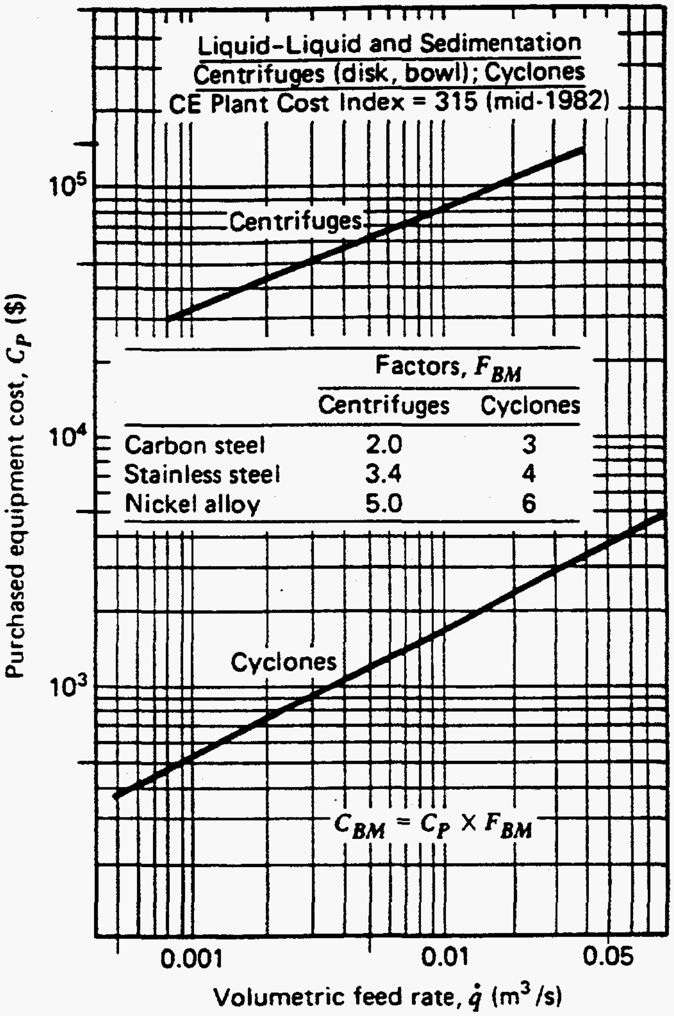
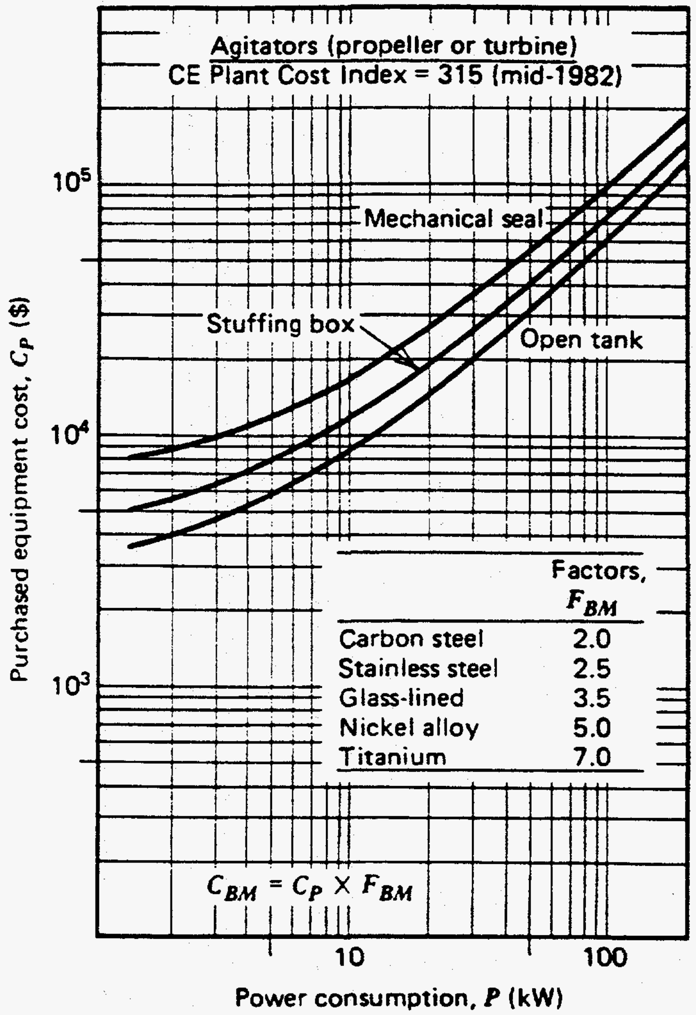


Figure 2-9 Ulrich's Fig. 5-55: Purchased Equipment Costs for Liquid-Liquid and Sedimentation Centrifuges and Cyclone Separators



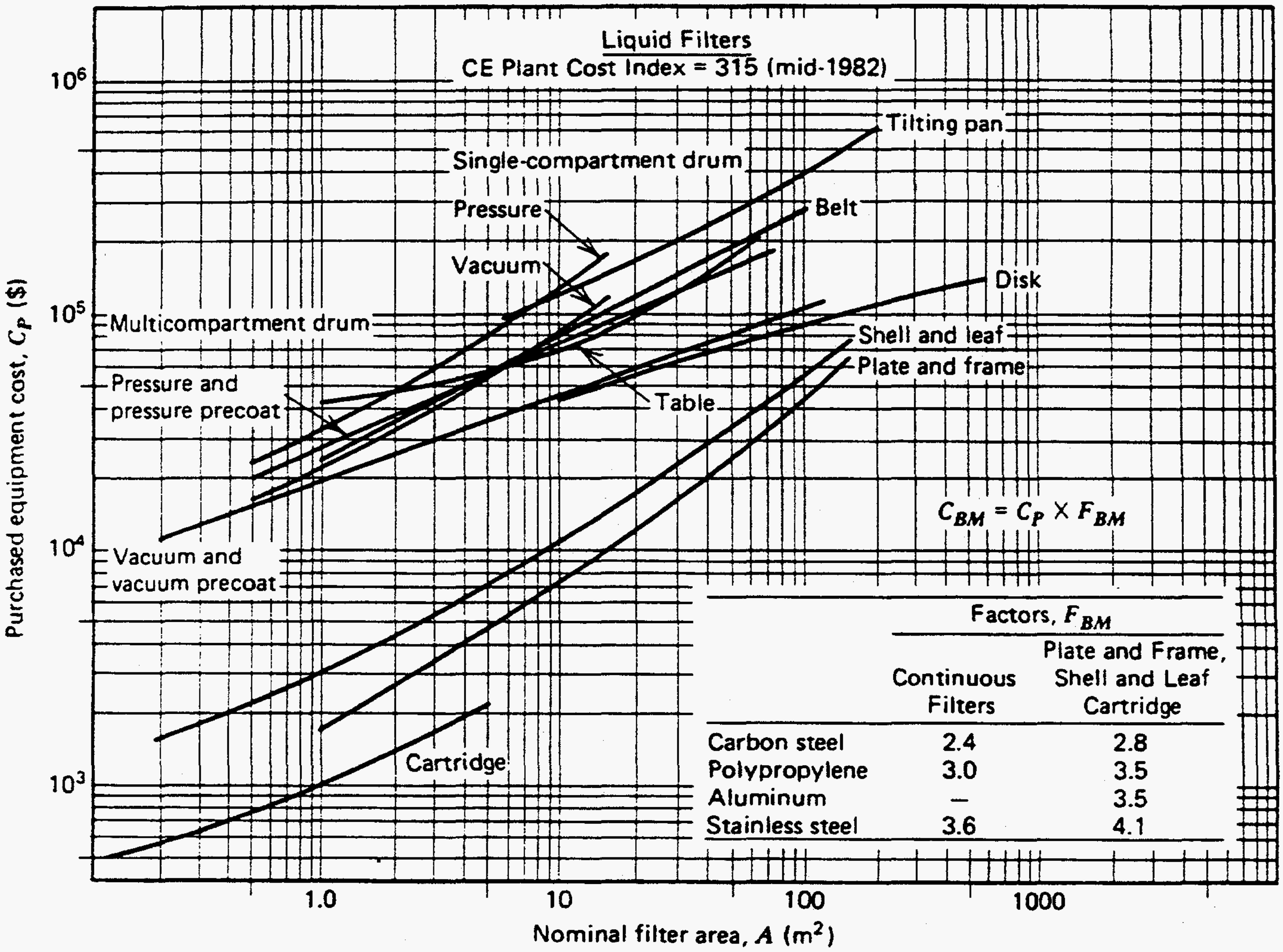
	Factors, F_{BM}	
	Centrifuges	Cyclones
Carbon steel	2.0	3
Stainless steel	3.4	4
Nickel alloy	5.0	6

Figure 2-10 Ulrich's Fig. 5-42: Purchased Equipment Costs for Propeller and Turbine Agitators



	Factors, F_{BM}
Carbon steel	2.0
Stainless steel	2.5
Glass-lined	3.5
Nickel alloy	5.0
Titanium	7.0

Figure 2-11 Ulrich's Fig. 5-57: Purchased Equipment Costs for Liquid Filters



$$C_{BM} = C_P \times F_{BM}$$

	Factors, F_{BM}	
	Continuous Filters	Plate and Frame, Shell and Leaf Cartridge
Carbon steel	2.4	2.8
Polypropylene	3.0	3.5
Aluminum	—	3.5
Stainless steel	3.6	4.1

Figure 2-12 Average Cost of NY Cargo Resid Fuel Oil
From Platt's September 14, 1993

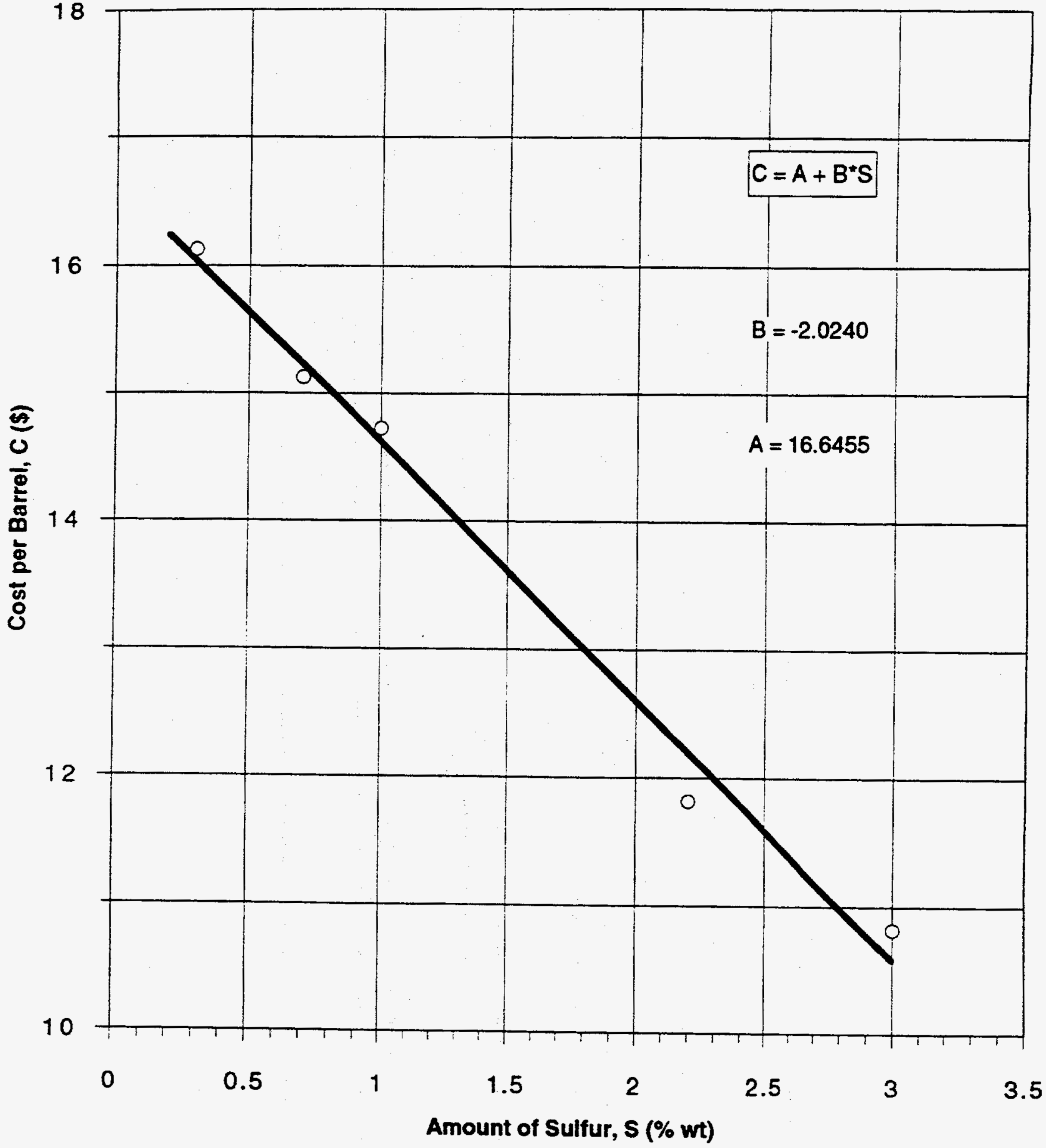


Figure 2-13 Average Cost of NY Cargo Fuel Oil No.6 From Platt's Oilgram Price Report of September 14, 1993

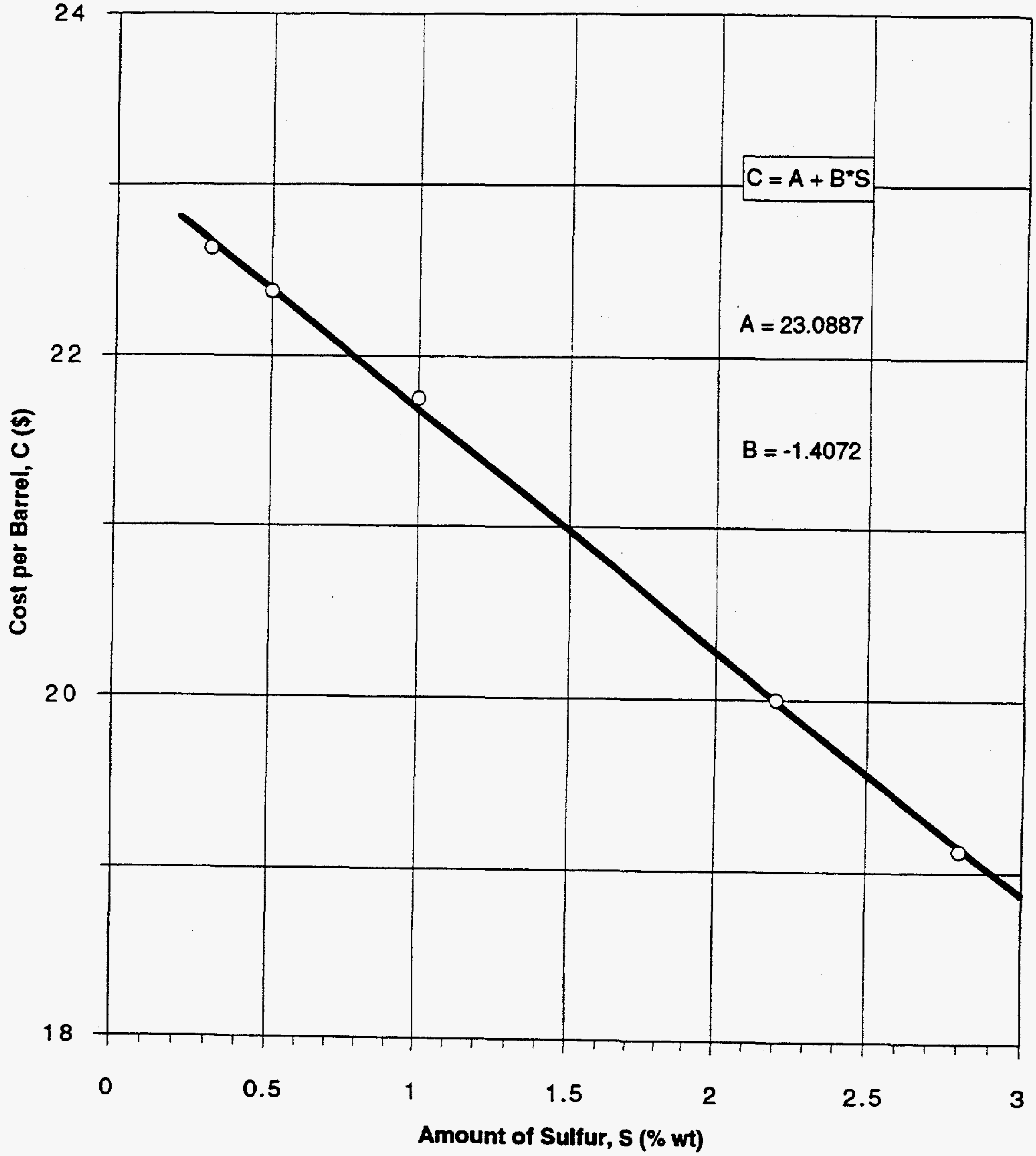


Figure 2-14 US East Coast Spot No. 6 Oil Cargo Prices (Bloomberg Oil Buyer's Guide 9/13/93)

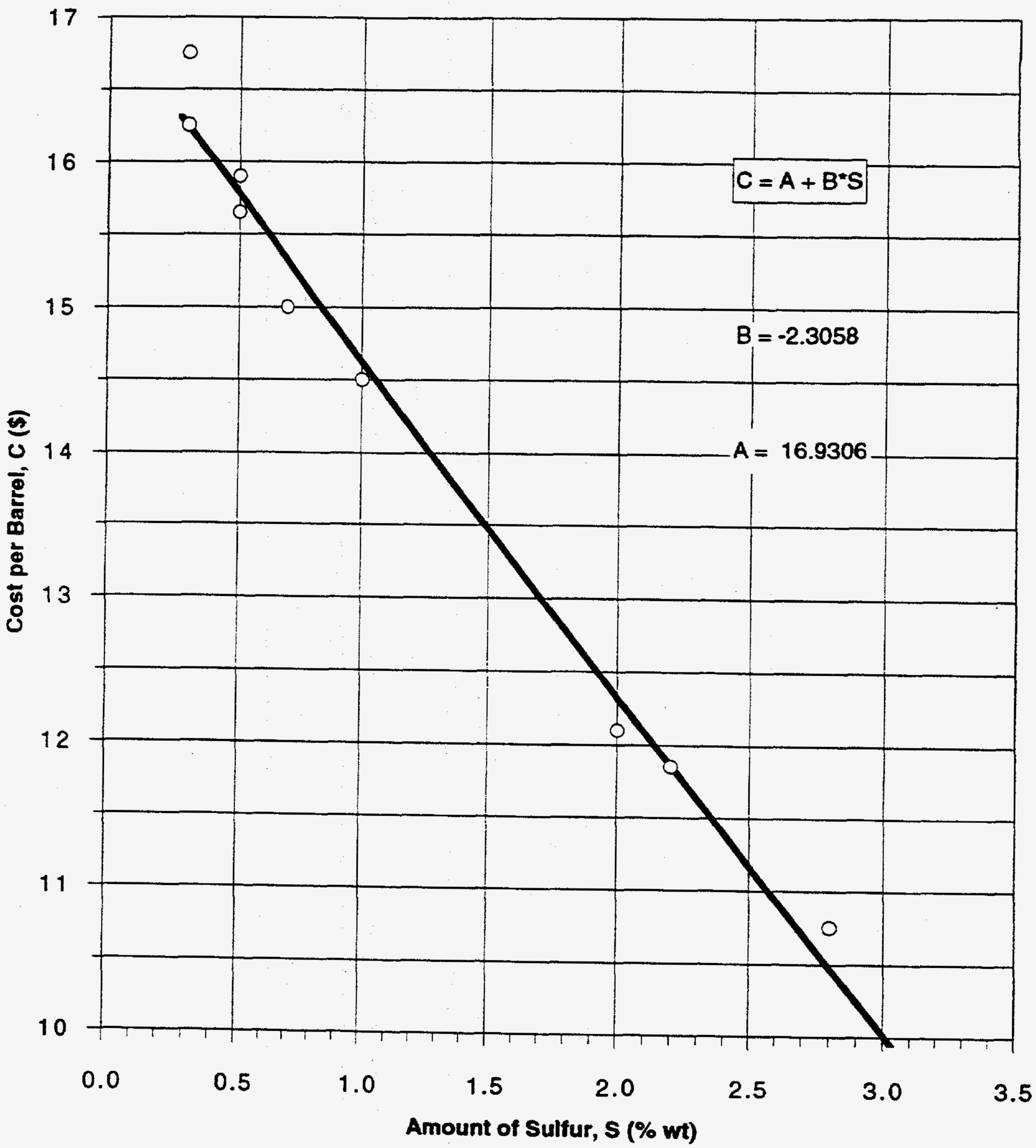


Figure 2-15 Petroleos de Venezuela Official FOB Postings #6 Residual Fuels Prices (Bloomberg Oil Buyer's Guide 9/13/93)

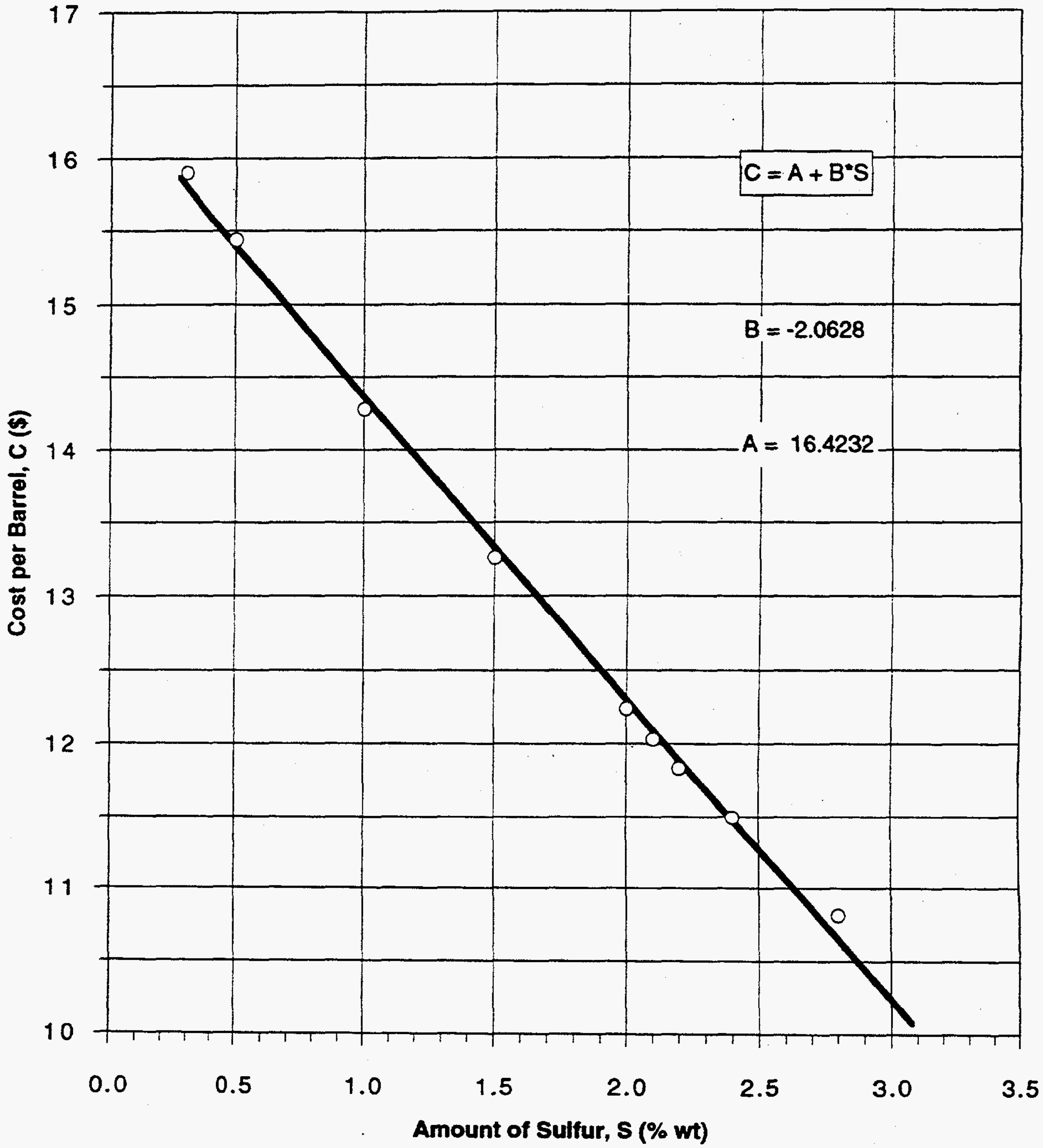


Figure 2-16 Estimated New York Contract Oil No.6 Cargo Prices (Bloomberg Oil Buyer's Guide 9/13/93)

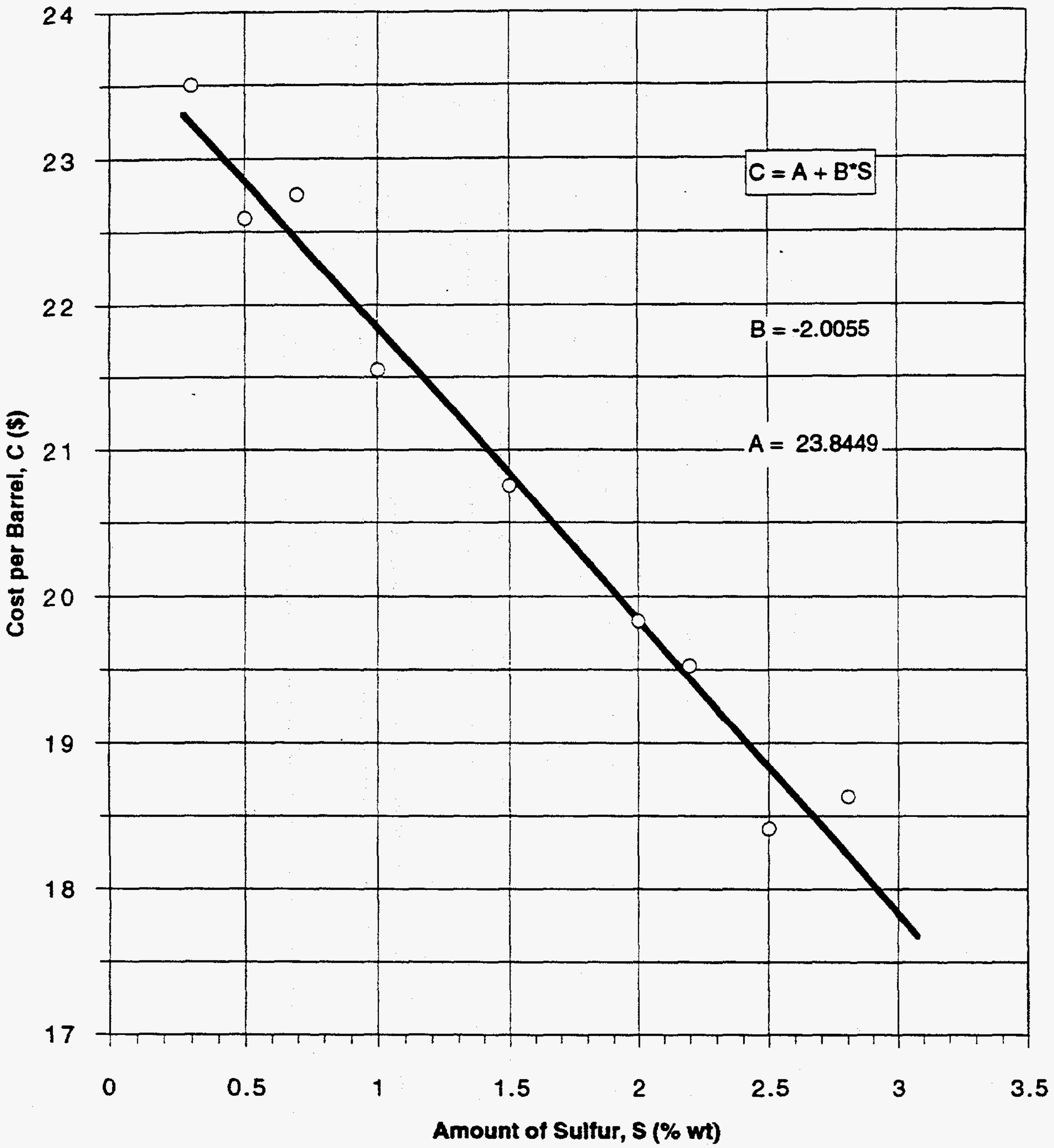


Figure 2-17 Average Prices of US East Coast Residual Fuel Oil No.6 Consumer Tankcar, FOB Supplier's Rack (Bloomberg Oil Buyer's Guide 9/13/93)

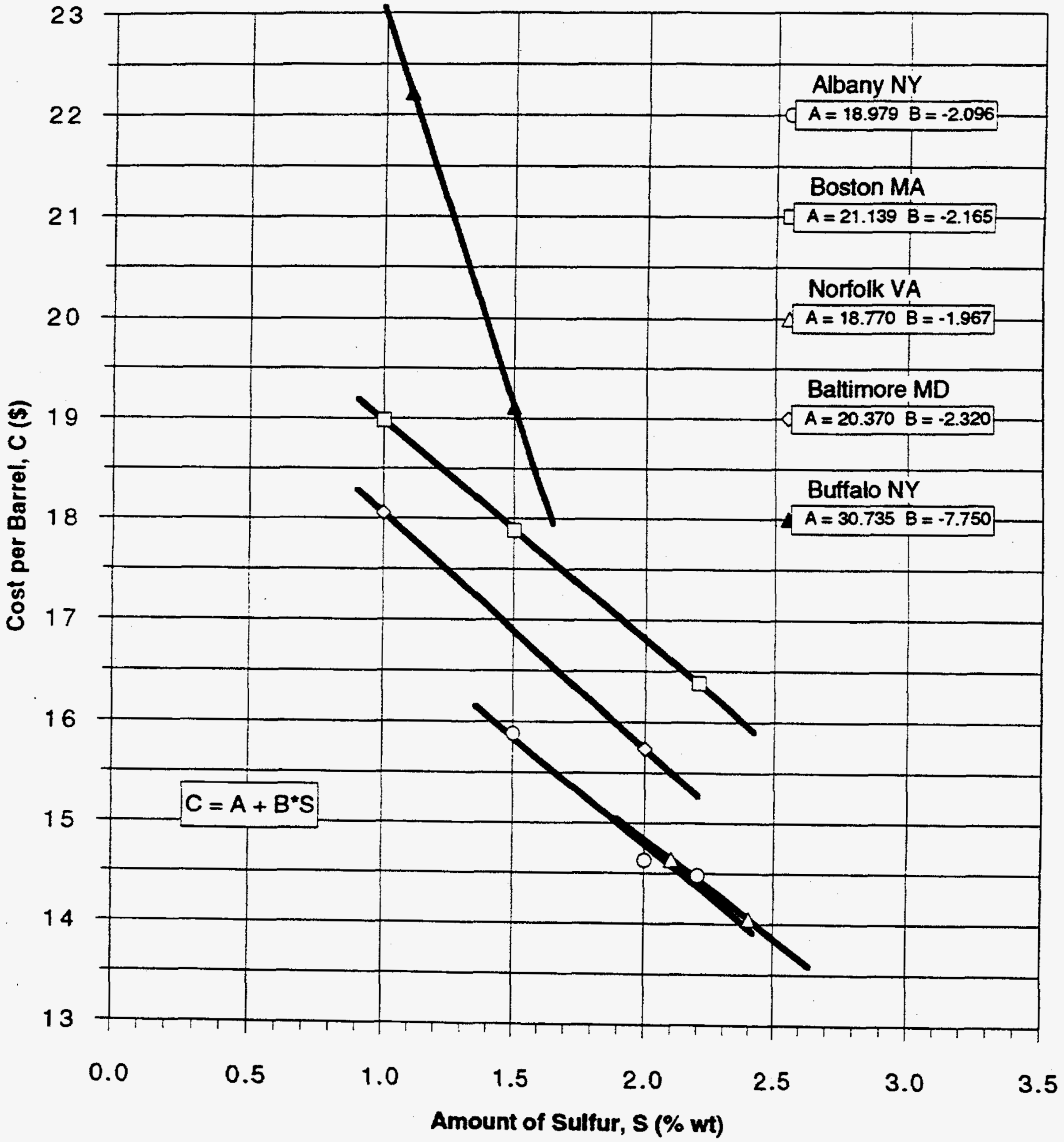


Figure 2-18 Northwest Europe Oil No.6 Cargo Prices

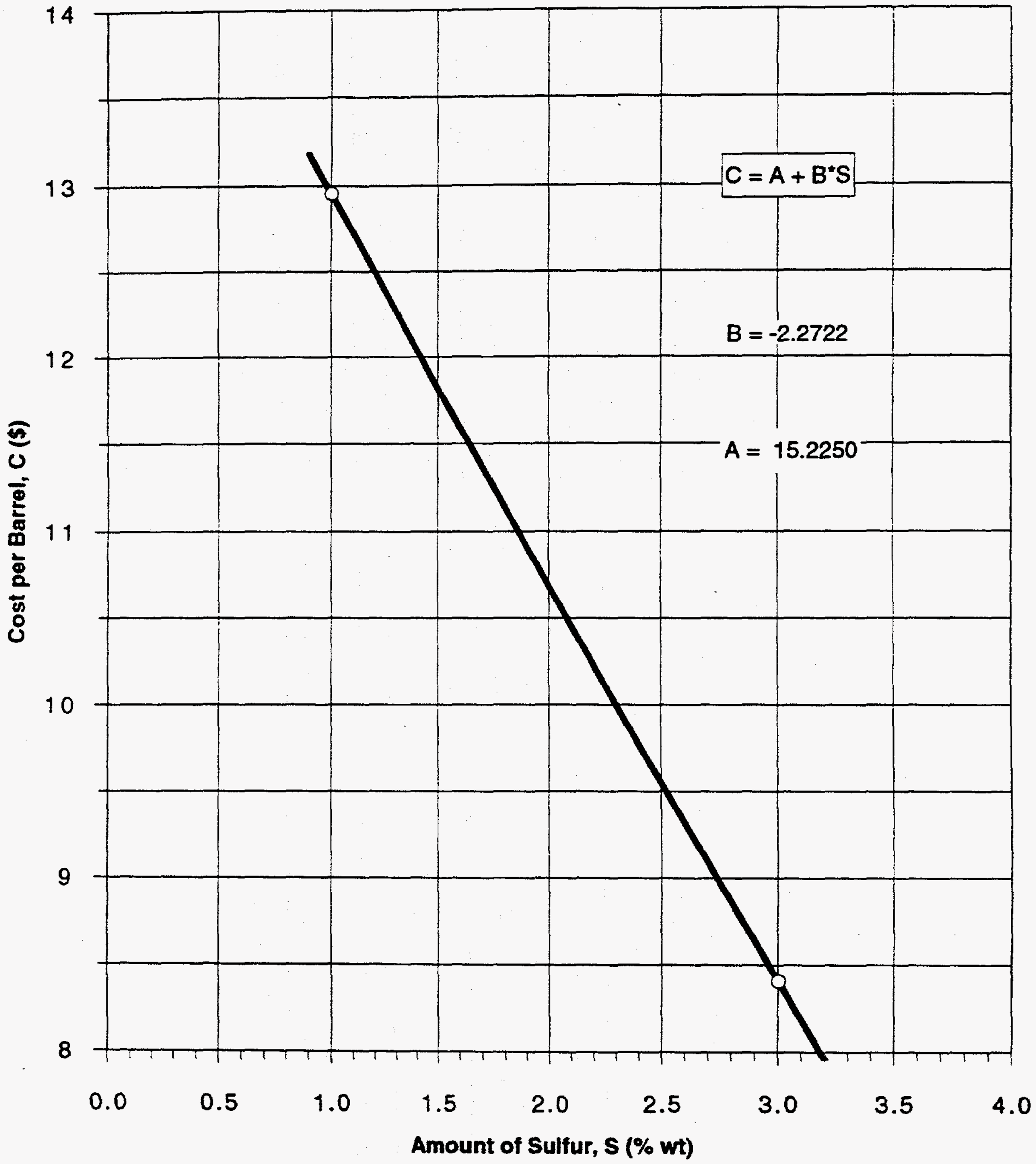
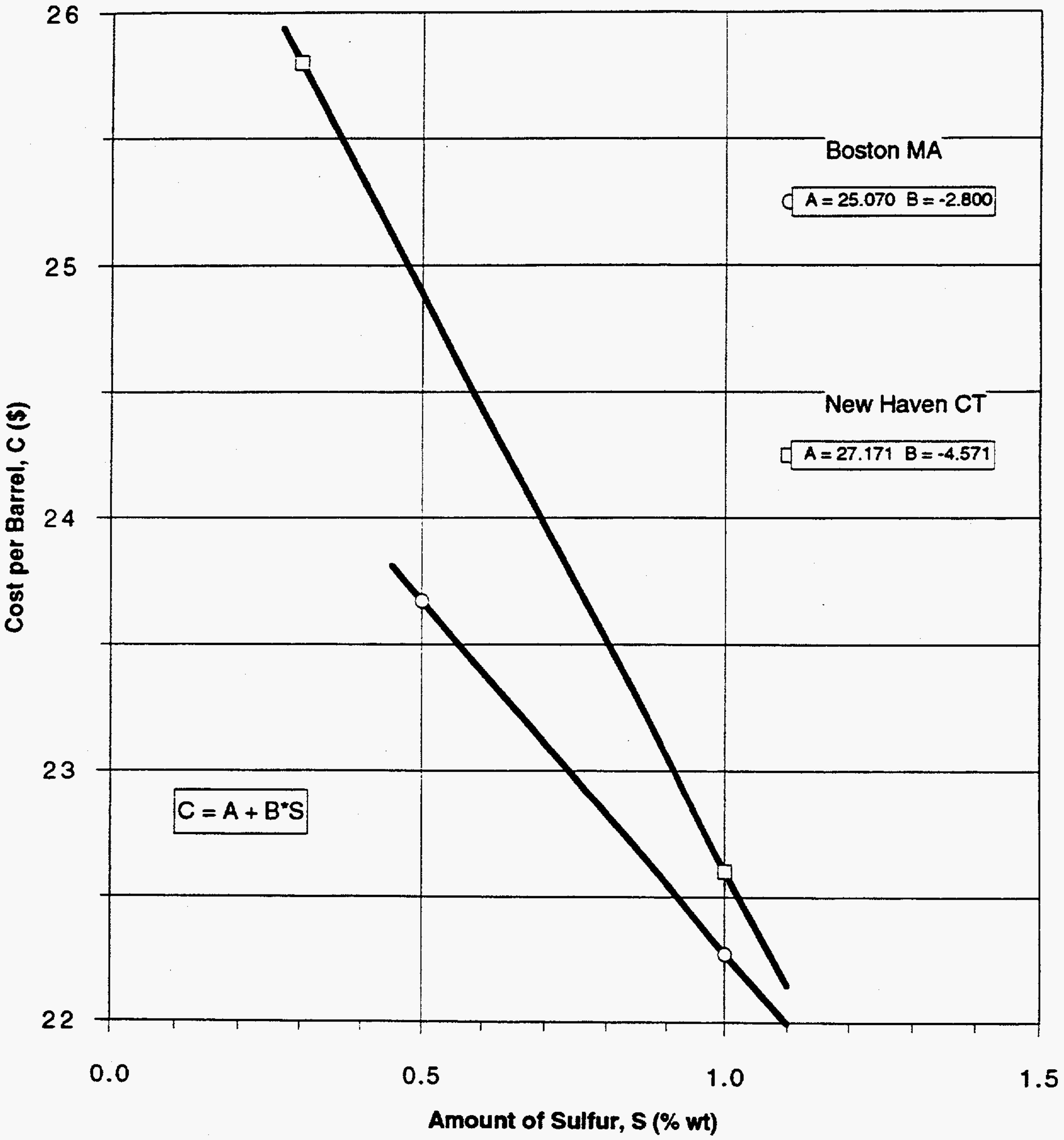


Figure 2-19 US East Coast Residual Fuel Oil No.4 Consumer Tankcar, FOB Supplier's Rack Average Prices (Bloomberg Oil Buyer's Guide 9/13/93)



3

Computer Modeling of the SFA Costing Methodology with Microsoft Excel Spreadsheet

3.1 Introduction

This section describes a computer model of the SFA costing methodology, including the estimation of equipment costs following charts and recommendations given in Ulrich's book. This computer model then is used in Section 4 to perform sensitivity analyses of the effects of several parameters on the net realization per barrel. The Microsoft Excel spreadsheet program made the calculations automatically.

The procedure for cost estimation is described in Section 2 and includes taking values from a set of charts from Ulrich's book. This computer implementation incorporates the information in Ulrich's charts by taking some points from a chart and interpolating them to automatically compute the y-value corresponding to a x-value.

3.2 Computerizing Ulrich's Costing Charts.

The procedure followed to computerize the information given by Ulrich's charts was to take some points from each chart and perform an appropriated interpolation to compute the y-value corresponding to any x-value in the range covered by the chart.

The method of interpolation used depends on the shape of the line in the chart. If the line is a straight one, a simple linear interpolation was used. When the line is not linear, a four-point piecewise Lagrangian interpolation was used.

The next two examples illustrate the interpolation procedure. The first example is a linear interpolation, and the second is a Lagrangian one.

3.2.1 Linear Interpolation

Consider Ulrich's chart to estimate the cost of a Bullet storage vessel, with pressure below 10 barg (Ulrich's Figure 5-61, p. 316, is reproduced in Section 2 of this report). A straight line is a good approximation in this case. Therefore, only the two extreme points are needed for the linear interpolation.

An enlarged copy of the chart was used to improve the precision of the method. Since the axes are in logarithmic scales, one should be careful to avoid mistakes. The coordinates of a point were calculated using measured distances to reference lines. The first point selected in Ulrich's Figure 5-61 is where the line crosses the C_p = \$2,000 gridline; this corresponds to a volume of $V = 1.33\ m^3$. The other end-point has coordinates $V = 1{,}535\ m^3$ and C_p = \$167,880.

Let $x_i = \log(V_i)$ and $y_i = \log(C_{pi})$, with i = 1, 2. Therefore, the value $y = \log(C_p)$ corresponding to a given $x = \log(V)$ is computed by a simple linear interpolation as follows

$$y = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1) \qquad (3\text{-}1)$$

where

$$x_1 = \log(V_1) = \log(1.33) \qquad (3\text{-}2a)$$
$$y_1 = \log(C_{p1}) = \log(2000) \qquad (3\text{-}2b)$$
$$x_2 = \log(V_2) = \log(1535) \qquad (3\text{-}2c)$$
$$y_2 = \log(C_{p2}) = \log(167880) \qquad (3\text{-}2d)$$
$$x = \log(V) \qquad (3\text{-}2e)$$
$$y = \log(C_p) \qquad (3\text{-}2f)$$

Hence, the sequence of calculations for a given V is: 1) compute $x = \log(V)$; 2) using eqn. 3-1, compute y; 3) compute C_p by

$$C_p = 10^y \qquad (3\text{-}3)$$

This procedure is implemented in a MS Excel spreadsheet and the calculation performed automatically. For example, let $V = 300\ m^3$. Therefore, from eqn. 3-1 it follows that:

$$y = \log(2000) + \left[\frac{\log(167880)-\log(2000)}{\log(1535)-\log(1.33)}\right]\left[\log(300)-\log(1.33)\right]$$

which gives y = 4.7796, and C_p = $60,194.

Figure 3-6 shows a chart computed by MS Excel, using the procedure described above.

3.2.2 Nonlinear Interpolation

Consider Ulrich's chart for the cost of a motionless mixer (Ulrich's Figure 5-41, p. 306, reproduced at Section 2). This is a nonlinear line. In this case, a four-point Lagrangian interpolation is used. First, some points were taken from the line; their coordinates are shown in Table 3-1 below.

Table 3-1 Data points taken from Ulrich's Figure 5-41 for estimating the cost of motionless mixers.

Point #	D (m)	Cp ($)	x = log(D)	$y = \log(C_p)$
1	0.0125	200.	-1.9031	2.30103
2	0.05	500.	-1.3010	2.69897
3	0.096	1000.	-1.0177	3.00000
4	0.2495	4000.	-0.6029	3.60206
5	0.55	15760.	-0.2596	4.19756

The four-point Lagrangian interpolation method fits a third degree polynomial passing through four points. This polynomial is used to compute intermediate values. For the example above, a first polynomial, P_1, is fitted to the first 4 data points, points 1, 2, 3 and 4 on Table 3-1. Polynomial P_1 then is used to compute intermediate values in the interval between points 1 and 2, and in the interval between points 2 and 3. For the interval between points 3 and 4, a second polynomial is fitted, P_2, to the points 2, 3, 4 and 5. Finally, polynomial P_2 is used for the interval between points 4 and 5.

Four points in the x-axis define a central interval and two lateral intervals. Except for the end intervals, the four-point Lagrangian interpolation uses the polynomial to compute values in the central region.

A Lagrangian polynomial, $L_i(x)$, associated with x_i is defined as follows

$$L_i(x) = \prod_{\substack{j=1 \\ j \neq i}}^{n} \frac{(x - x_j)}{(x_i - x_j)} \qquad (3\text{-}4)$$

where n is the number of points considered at a time, in our case n = 4, i is the point with which the Lagrangian polynomial is associated. For example, for i = 2 the Lagrangian polynomial becomes:

$$L_2(x) = \frac{(x-x_1)(x-x_3)(x-x_4)}{(x_2-x_1)(x_2-x_3)(x_2-x_4)} \qquad (3\text{-}5)$$

From eqn. 3-5, we one can verify that $L_2(x_1) = L_2(x_3) = L_2(x_4) = 0$ and $L_2(x_2) = 1$. Therefore, the third degree polynomial $L_2(x)$ has the value of 1 at x_2 and the value of zero at x_1, x_3 and x_4. Analogously, $L_j(x_i) = 1$ for $i = j$ and $L_j(x_i) = 0$ for $i \neq j$.

Let y_i be the ordinate corresponding to x_i. Therefore, the function $y_2L_2(x)$ has the value of y_2 at x_2, and is zero at x_1, x_3, and x_4. Consequently, the polynomial $P_1(x)$, which passes through points 1, 2, 3, and 4, can be written as follows:

$$P_1(x) = y_1L_1(x) + y_2L_2(x) + y_3L_3(x) + y_4L_4(x) \qquad (3\text{-}6)$$

Notice that $P_1(x_i) = y_i$, as is required. Polynomial $P_1(x)$ is used to compute y-values in the interval $x_1 \leq x \leq x_3$, as explained above.

Polynomial $P_2(x)$ is computed is a similar way. In this case the 4 points to be used are 2, 3, 4 and 5. For example, the Lagrangian polynomial associated with point 3 is

$$L_3'(x) = \frac{(x-x_2)(x-x_4)(x-x_5)}{(x_3-x_2)(x_3-x_4)(x_3-x_5)} \qquad (3\text{-}7)$$

and $P_2(x)$ is

$$P_2(x) = y_2L_2'(x) + y_3L_3'(x) + y_4L_4'(x) + y_5L_5'(x) \qquad (3\text{-}8)$$

$P_2(x)$ is used to compute y-values in the interval $x_3 \leq x \leq x_5$.

This procedure computes y-values by the weighted sum of Lagrangian polynomials. In this case, because the chart is in logarithmic scales, the computed y-value needs to be transformed back to the original C_p.

The sequence of calculations to compute the C_p for a given D are: 1) select a some representative data points in the graph; 2) in a tabular form, collect the coordinates of the original variables, i.e. D and C_p in this case, as in Table 3-1; 3) compute $x_i = \log(D_i)$ and $y_i = \log(C_{pi})$; 4) compute $x = \log(D)$; 5) using the four-point Lagrangian method compute y = P(x), using the appropriate polynomial; and 6) compute $C_p = 10^y$.

As an example of calculation, let D = 0.5 m. Because this point is in the interval between points 4 and 5, use polynomial $P_2(x)$. The calculated y-value is obtained by applying eqs. 3-7 and 3-8, with the values of x_i and y_i as shown in Table 3-1. This results in y = 4.122663, and consequently Cp = $13,264.

The procedure described above is implemented in Excel with the help of an Excel macro. This user-defined macro was called LAGRANGE4 and takes three arguments. The first argument is a y-vector containing all y-values for the selected points, i.e. y_1, y_2, y_3, y_4 and y_5, the second argument is a x-vector which contains the corresponding x-values, the third argument is any x-value between the minimum and maximum x-values in the x-vector. The macro computes the corresponding y-value, using the four-point Lagrangian interpolation procedure.

Figure 3-2 shows a chart computed by the Lagrangian interpolation, using the data in Table 3-1. There is good agreement with Ulrich's Figure 5-41, shown in Section 2. Figures 3-1 to 3-8 are charts computed by interpolations of all the Ulrich's charts needed for the automatic computation of equipment costs. Each chart indicates the data points used for the interpolation.

3.3 Computation of the Net Realization with Excel

Following the procedure described in Section 2 and using the interpolation method described in Section 3.2, an Excel spreadsheet was created to automatically calculate of the net realization. This Excel spreadsheet is shown in Tables 3-2, 3-3, and 3-4.

The input parameters, i.e. the parameters with chosen values, are indicated with the word "input." References to Ulrich's figures also are indicated. The sequence of calculation is similar to the one followed in Section 2.

If a different value is used for an input variable, Excel will automatically perform all calculations, giving in a new value for the net realization. This feature of Excel makes the calculation of sensitivity analysis feasible.

The parameters used in this example are for the base case (Table 1-2). The feed type is Resid Fuel Oil with 3 wt% S. The net realization per barrel is $0.059.

Figure 3-1 Computerized Empirical Functional Relationship "Cone Roof," CR(V), of Purchased Equipment Cost, Cp, for Storage Vessels, to Volume, V (Ulrich Figure 5-61, Cone Roof)

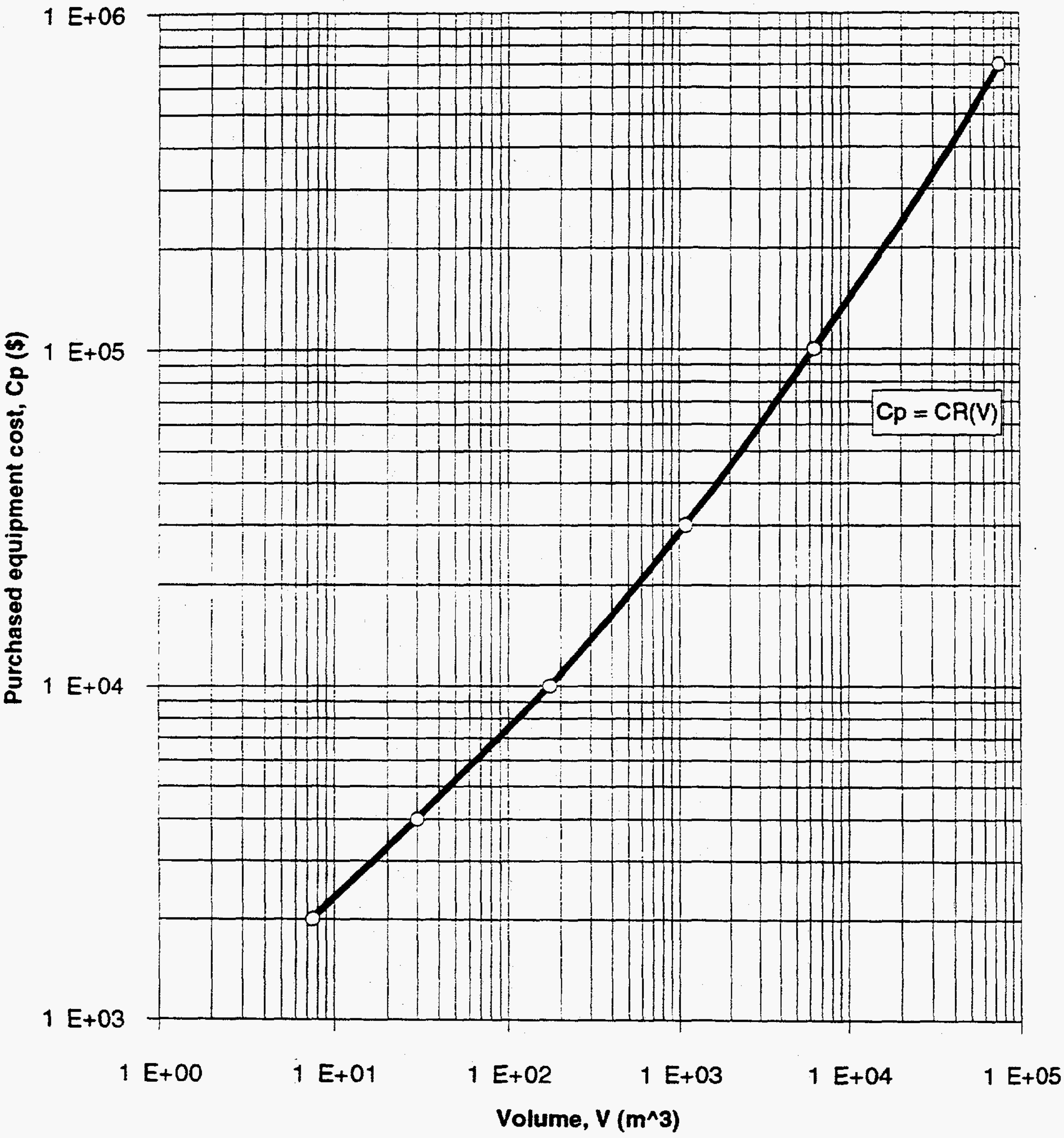


Figure 3-2 Computerized Empirical Functional Relationship "Motionless Mixer," MLM(D), of Purchased Equipment Cost, Cp, for Motionless Mixer, to Diameter, D (Ulrich Figure 5-41)

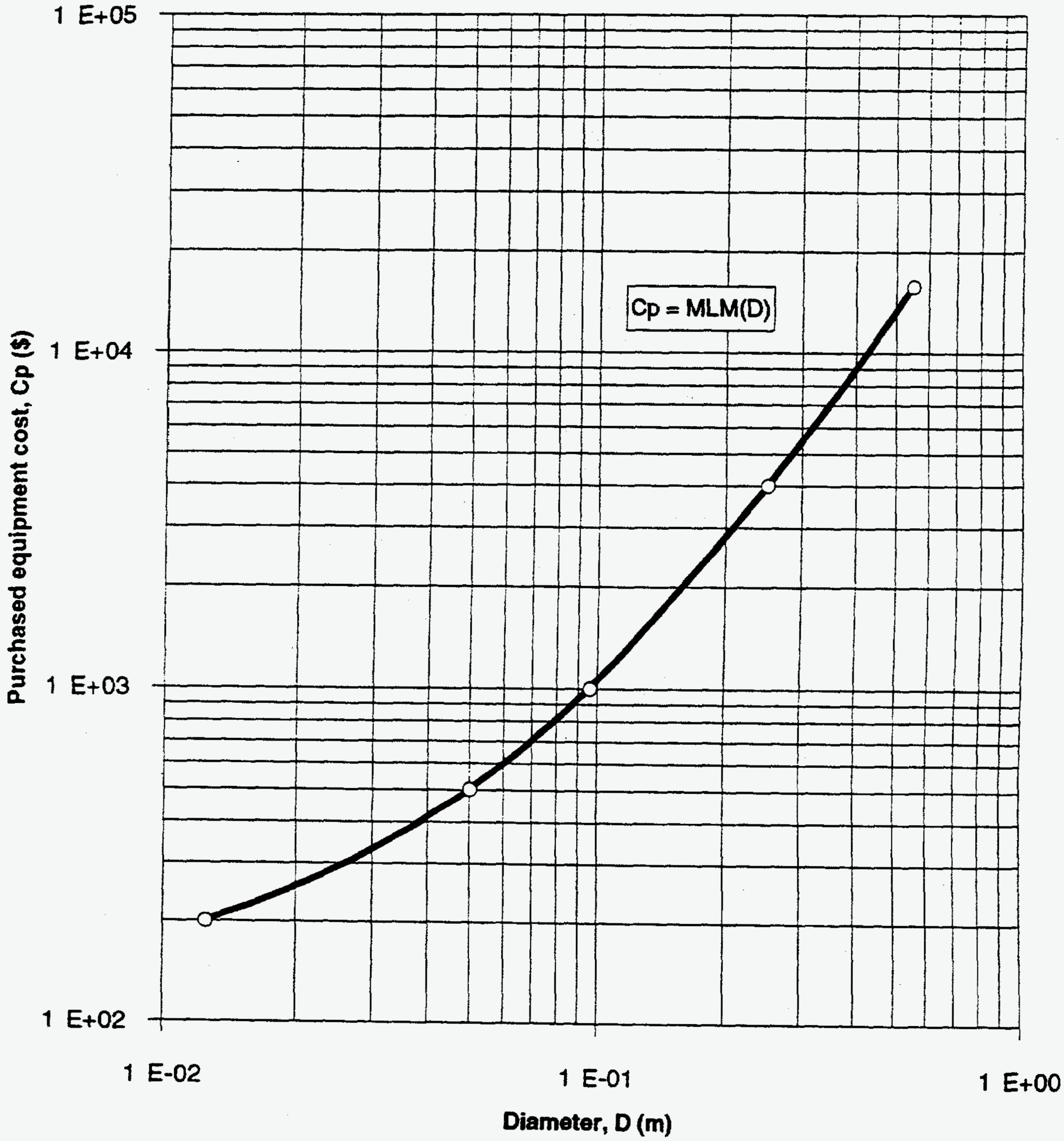


Figure 3-3 Computerized Empirical Functional Relationship "Centrifugal Pump," CP(ws), of Purchased Equipment Cost, Cp, for Centrifugal Pumps, to Pump Shaft Power, ws (Ulrich Fig. 5-49)

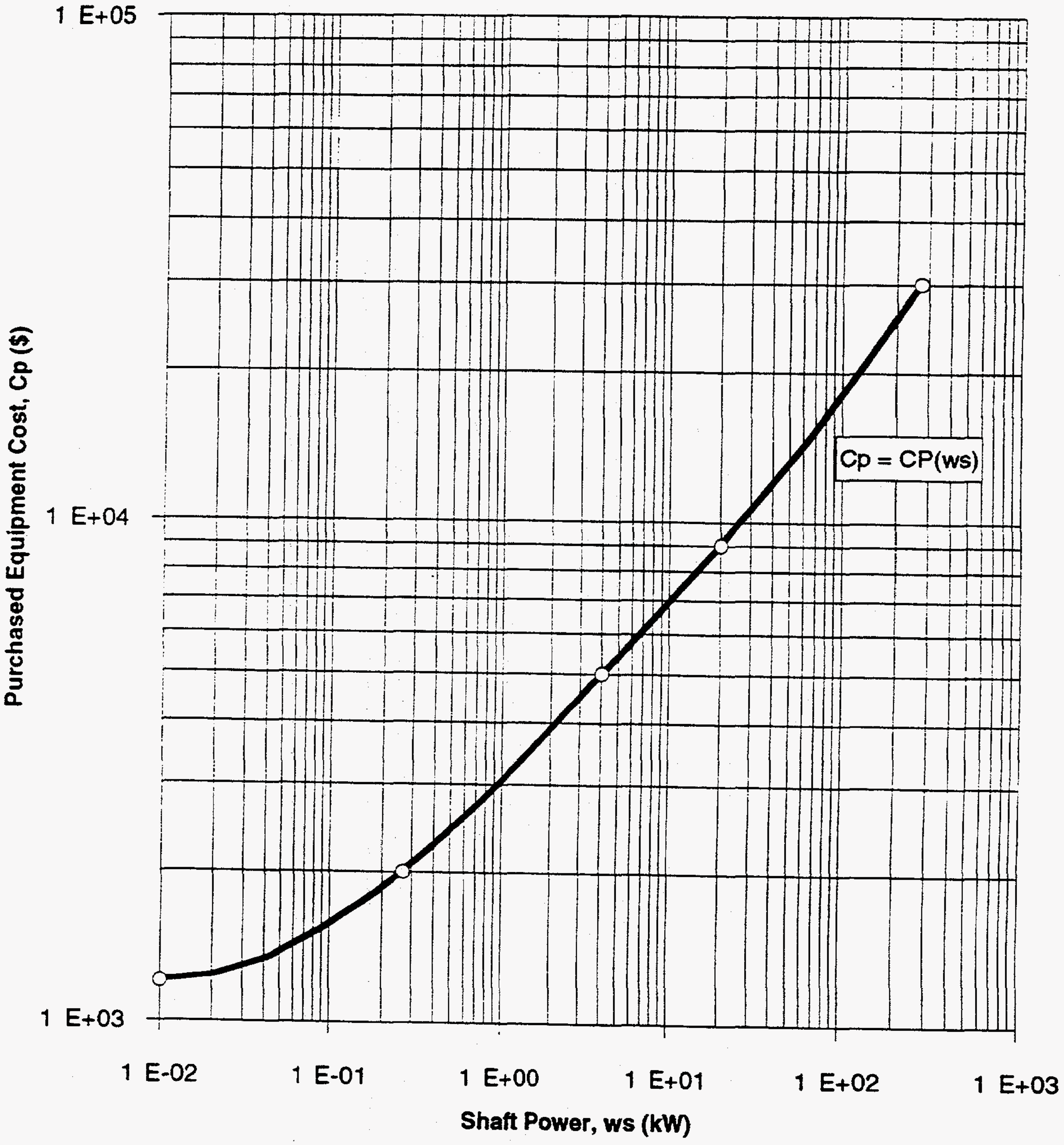


Figure 3-4 Computerized Emperical Functional Relationship "Material x Pressure Factor," MPF(FpxFm) of Bare Module Factor, FBM, for Pumps, to the Product of Material Factor x Pressure Factor, Fp x Fm (Ulrich Figure 5-51)

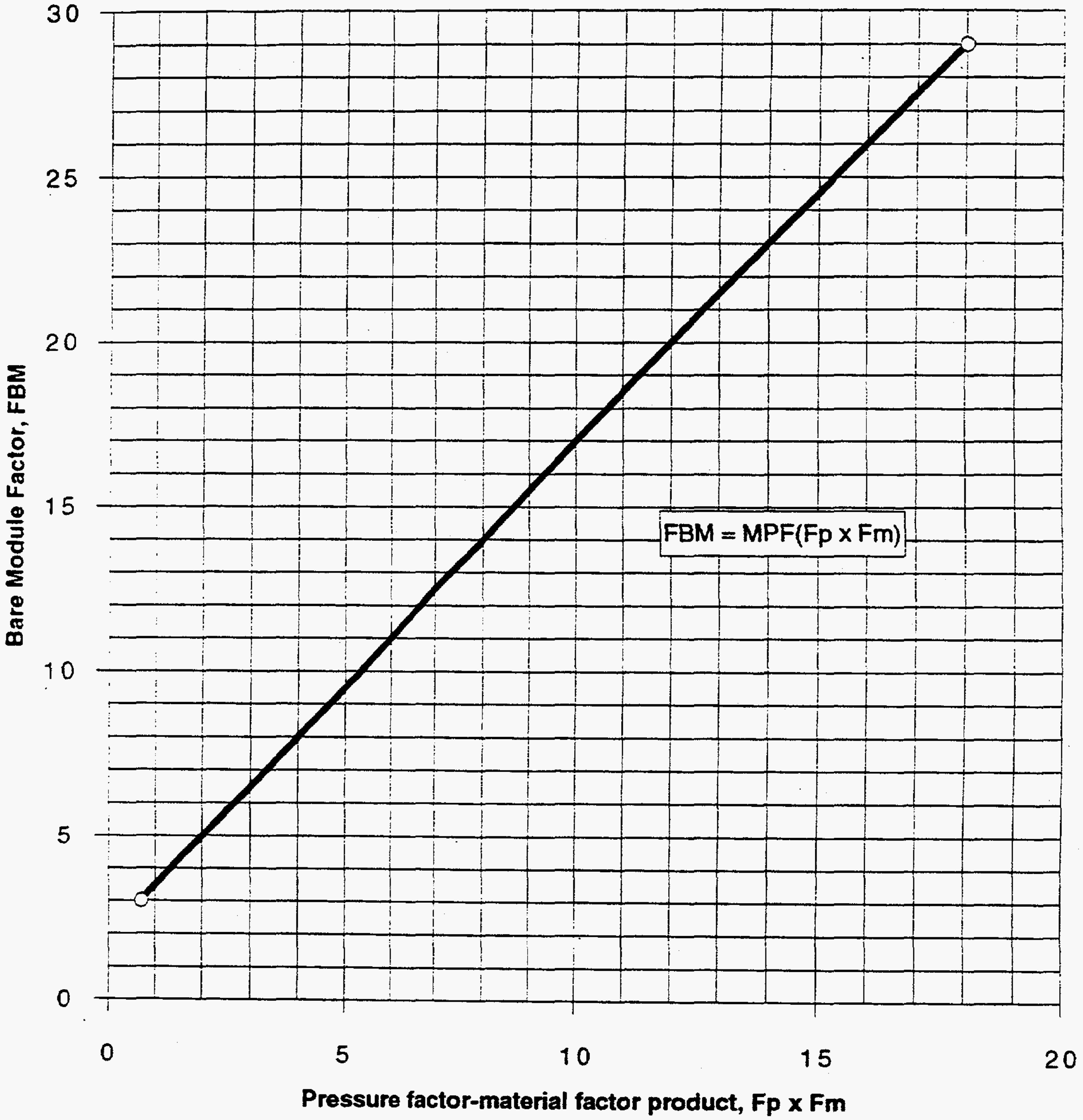


Figure 3-5 Computerized Empirical Functional Relationship "Sedimentation Centrifuge," SC(q), of Purchased Equipment Cost, Cp, for Sedimentation Centrifuge, to Volumetric Feed Rate, q (Ulrich Figure 5-55)

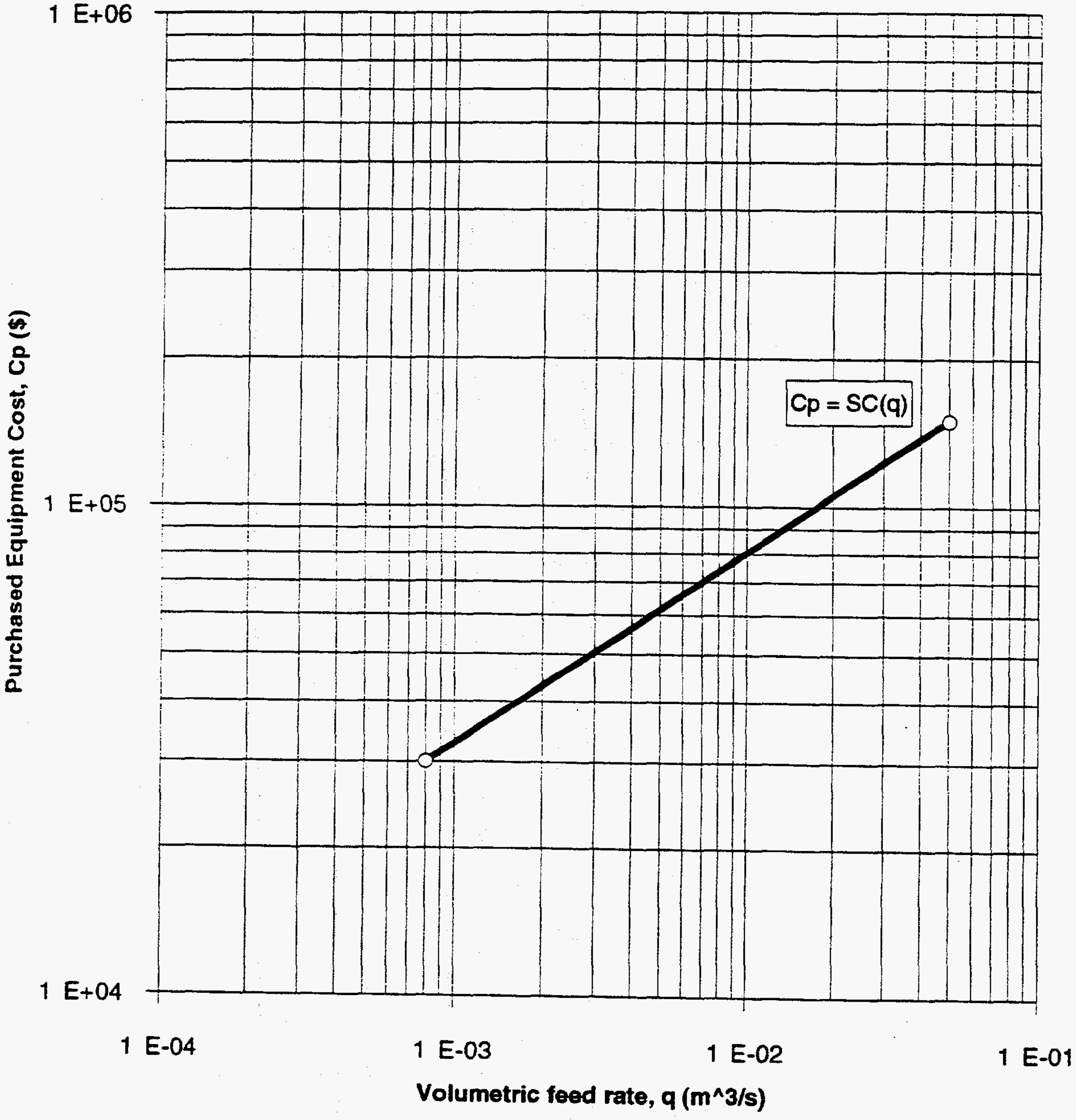


Figure 3-6 Computerized Empirical Functional Relationship "Bullet 0-10 barg," B0-10(V), of Purchased Equipment Cost, Cp, for Storage Vessels to Volume, V (Ulrich Fig. 5-61, Bullet 0-10 barg)

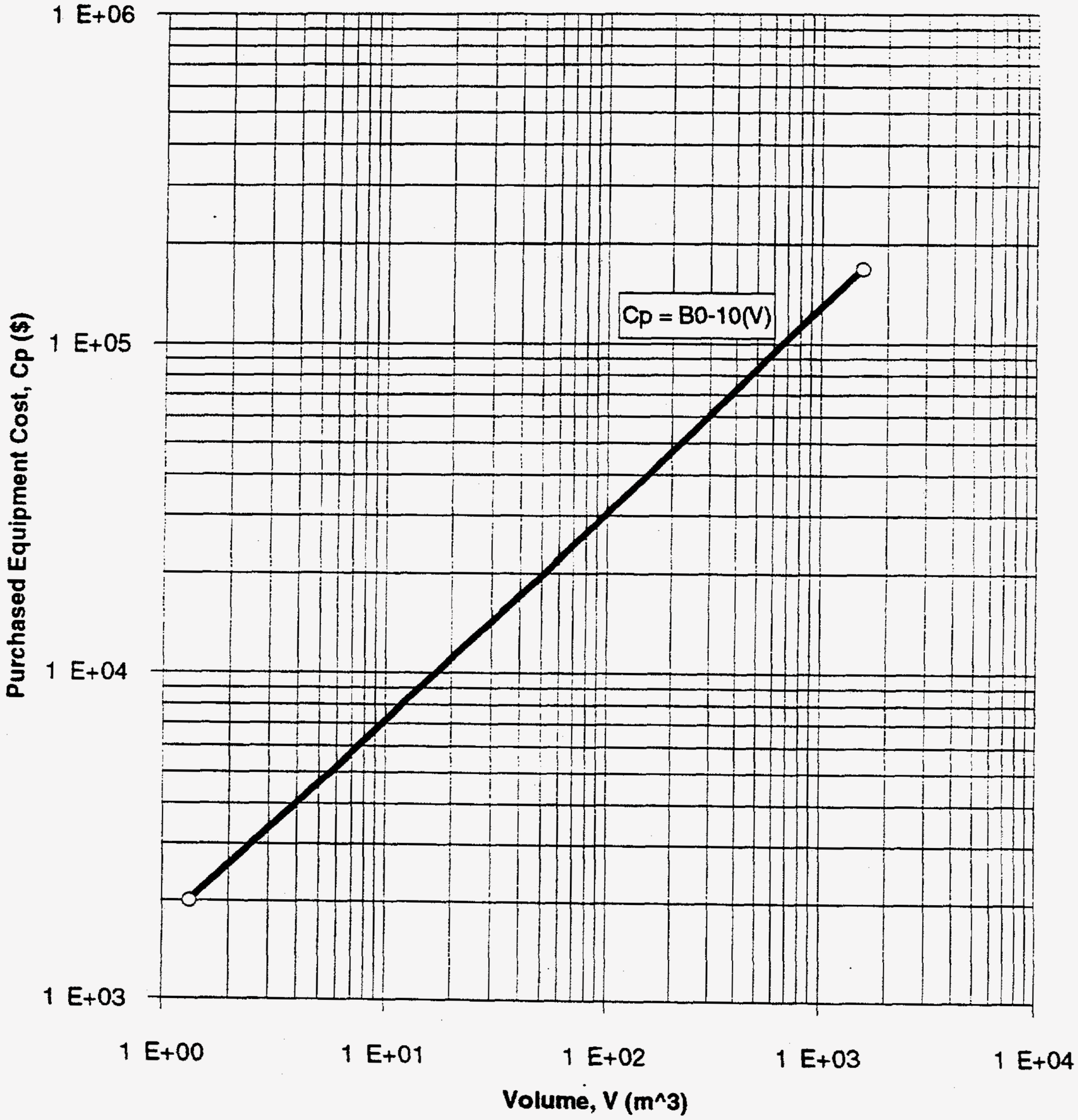


Figure 3-7 Computerized Empirical Functional Relationship "Stuffing Box," SB(P), of Purchased Equipment Cost, Cp, for Agitators, to Power, P (Ulrich Figure 5-42, Stuffing box)

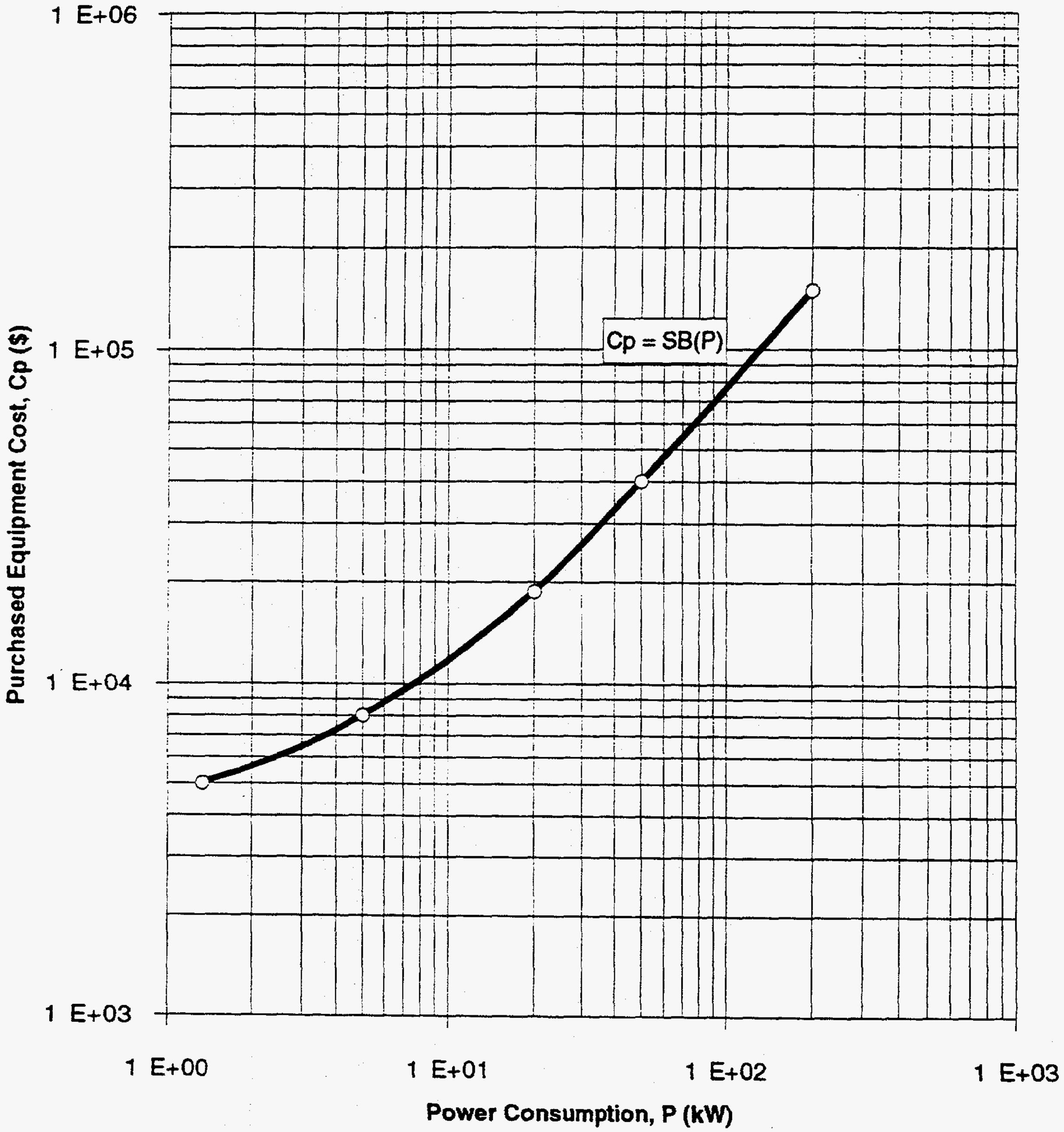


Figure 3-8 Computerized Empirical Functional Relationship "Plate and Frame," PF(A), of Purchased Equipment Cost, Cp, for Liquid Filters, to Nominan Filter Area, A (Ulrich Figure 5-57, Plate and Frame)

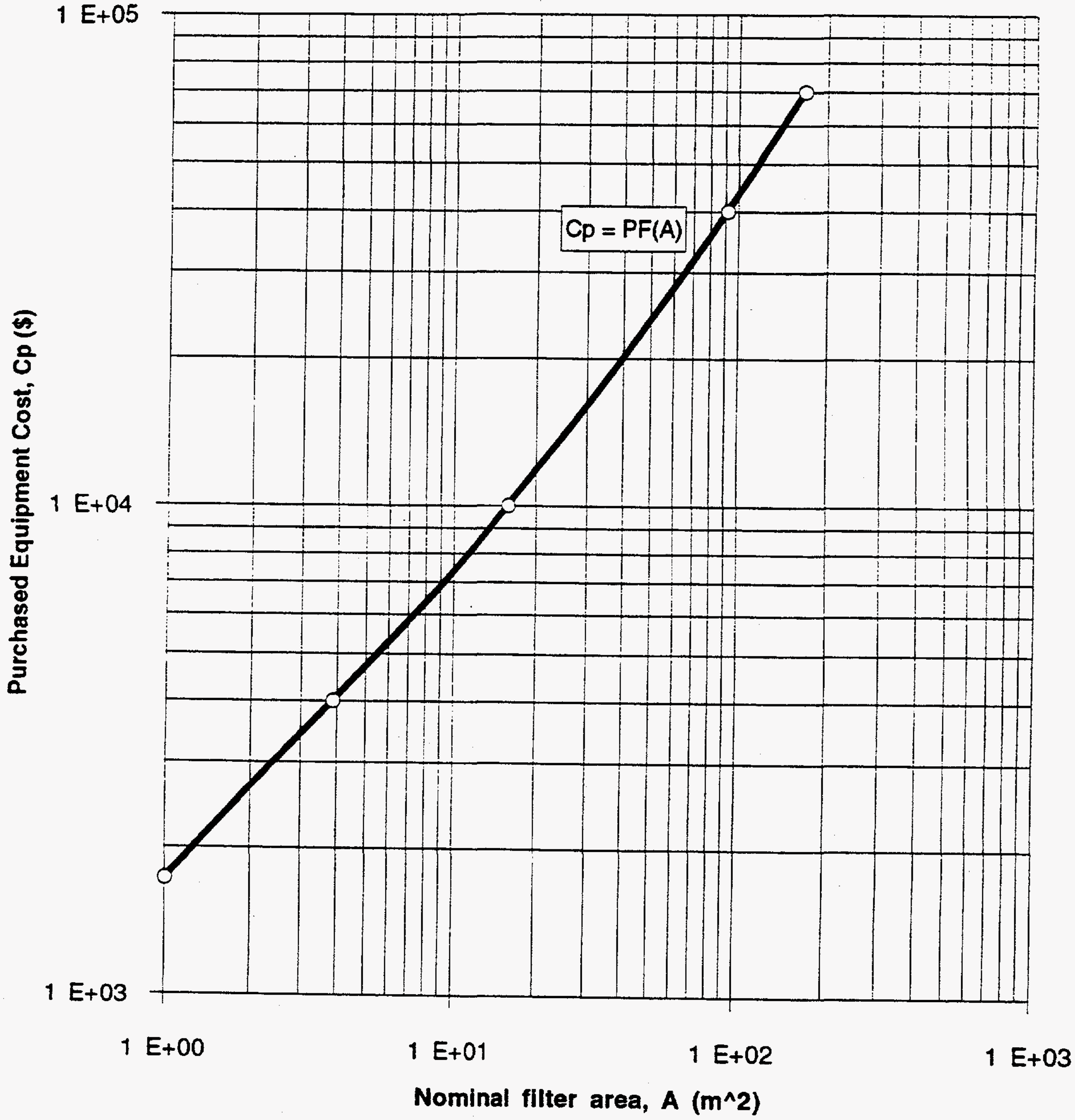


Figure 3-9 Computerized Empirical Functional Relationship "Centrifugal Pumps," CP(pi), of Pressure Factor, Fp, for Centrifugal Pumps, to Suction Pressure, pi (Ulrich Figure 5-50)

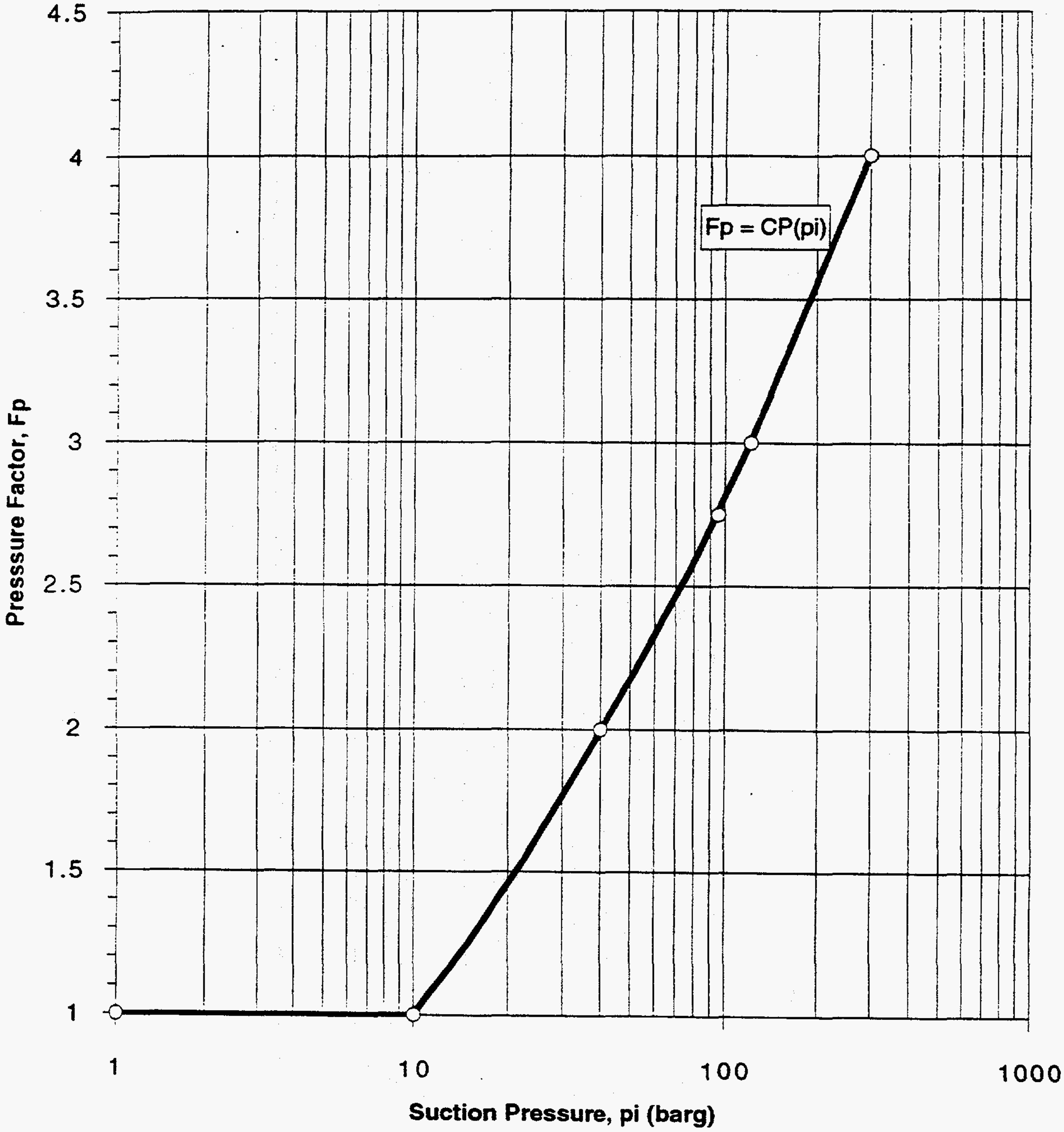


Table 3-2 Computerized Cost Estimation of Biochemical Upgrading of Heavy Crudes

Battery Limit Process Equipment Costs (BLE)			
	BLE=	**$793,840**	
1 Oil Tank	**CBM=**	**$93,359**	**Notes**
Oil to be treated per batch		250,000 gal	input
Volumetric ratio bact/oil	rv=	0.60	input
Bacteria culture per batch		150,000 gal	
Total reaction medium		400,001 gal	
Fraction of tank normally used		0.8	input
Volume of oil tank (gal)		500,001 gal	
Volume of oil tank (m3)		1892.71 m3	
Cp (purchase cost)	Cp=	$43,090	U. Fig. 5-61, Cone roof line
Installation factor (carbon steel)	FBM=	1.9	U. Fig. 5-61, Carbon steel
Bare module capital cost (1982)	CBM=	$81,871	
Factor to calc. cost at mid. 1993		1.1403	input
Bare module capital cost (1993)	CBM=	$93,359	
2 Motionless Mixer	**CBM=**	**$43,862**	
Assumed diameter of equipment	D=	0.5 m	input
Cp (purchase cost)	Cp=	$13,264	U. Fig. 5-41
Installation factor (stainless steel)	FBM=	2.9	U. Fig. 5-41
Bare module capital cost (1982)	CBM=	$38,465	
Bare module capital cost (1993)	CBM=	$43,862	
3 Pump (1)	**CBM=**	**$49,056**	
Mass flow rate	m=	1030 ton/hr	input
Mass flow rate	m=	286.1 kg/s	
Specific gravity of fluid	sp.gr.=	0.80	input
Differential pressure	Δp=	0.5 atm	input
Efficiency	ε=	0.6	input
Shaft power	ws=	30.2 kW	Ulrich p. 67 eq. 4-3
Cp (purchase cost)	Cp=	$10,617	U. Fig. 5-49, Centrifugal
Material factor	FM=	1.4	U. Fig. 5-49, Cast Steel
Suction pressure	pi=	<10 barg	
Pressure factor	Fp=	1.0	
Pressure factor-material factor	Fp*FM=	1.4	U. Fig. 5-50
Bare module factor	FBM=	4.05	U. Fig. 5-51
Bare module capital cost (1982)	CBM=	$43,020	
Bare module capital cost (1993)	CBM=	$49,056	
4 Pump (2)	**CBM=**	**$39,963**	
Mass flow rate	m=	770 ton/hr	input
Mass flow rate	m=	213.9 kg/s	
Specific gravity of fluid	sp.gr.=	1	input
Differential pressure	Δp=	0.5 atm	input
Efficiency	ε=	0.6	input
Shaft power	ws=	18.1 kW	Ulrich p. 67 eq. 4-3
Cp (purchase cost)	Cp=	$8,649	U. Fig. 5-49, Centrifugal
Material factor	FM=	1.4	U. Fig. 5-49, Cast Steel
Suction pressure	pi=	<10 barg	
Pressure factor	Fp=	1.0	
Pressure factor-material factor	Fp*FM=	1.4	U. Fig. 5-50
Bare module factor	FBM=	4.05	U. Fig. 5-51
Bare module capital cost (1982)	CBM=	$35,046	
Bare module capital cost (1993)	CBM=	$39,963	

Table 3-2 Computerized Cost Estimation of Biochemical Upgrading of Heavy Crudes (Continued)

5 **Sedimentation Centrifuge**	**CBM=**	**$328,658**		
Mass flow rate	m=	144	ton/hr	input
Mass flow rate	m=	40	kg/s	
Specific gravity	sp.gr.=	0.89		
Volumetric flow rate	q=	0.045	m3/s	
Cp (purchase cost)	Cp=	$144,108		U. Fig. 5-55
Installation factor (carbon steel)	FBM=	2		U. Fig. 5-55
Bare module capital cost (1982)	CBM=	$288,216		
Bare module capital cost (1993)	CBM=	$328,658		
6 **Preciptation Drum**	**CBM=**	**$137,540**		
Vessel volume	V=	50,000	gal	input
Vessel volume	V=	189.27	m3	
Purchase cost	Cp=	$45,068		U. Fig. 5-61, Bullet 0-10 barg
Installation factor, carbon steel	FBM=	1.9		U. Fig. 5-61
Bare module capital cost (1982)	CBM=	$85,630		
Bare module capital cost (1993)	CBM=	$97,645		
Agitator power (0.2V^0.8)	P=	13.3	kW	U. Table 4-16, axial turbine
Cp (purchase cost)	Cp=	$13,994		U. Fig. 5-42
Installation factor (stainless steel)	FBM=	2.5		U. Fig. 5-42
Bare module capital cost (1982)	CBM=	$34,986		
Bare module capital cost (1993)	CBM=	$39,895		
7 **Filter Press**	**CBM=**	**$29,234**		
Filter area	A=	10	m2	input
Cp (purchase cost)	Cp=	$7,325		U. Fig. 5-57, plate and frame
Installation factor (polypropylene)	FBM=	3.5		U. Fig. 5-57
Bare module capital cost (1982)	CBM=	$25,637		
Bare module capital cost (1993)	CBM=	$29,234		

Table 3-3 Aditional Input Values and Intermediate Results

Battery limit process equip.	BLE=	$793,840		
Electric cost rate		0.05	$/kWh	input
Average motor efficiencies		0.8		input
Electric power for pumps		60.3	kW	
Power for centrifuge & prec. drum		20.8	kW	
Stream days in a year		330	sd/yr	input
Working hours in a year		7,920	hours/yr	
Light. power (fraction of total power)		3%		input
Utilities cost	UT=	$20,491		
General facilities	GF=	$277,844		
Total facilities costs	TFC=	$1,092,175		
Engineering & home offices	E&HO=	$109,217		
Plant startup and minor revamp	PSU=	$54,609		
Process royalties	PR=	$21,843		
Number of batch cycles		50		calc. or input
Total mass of batch		1325	ton	
Duration per batch cycle		36.8	hours	input or calc.
Duration of product process		9.2	hours	
Set up time		2.0	hours	input
Time duration of a batch		48.0	hours	
Number of batches in a year		165.0	batches/yr	
Crude oil consumed per year		982,142.86	bbl/yr	
Sulfur in crude		3.00%	wt%	input
Cost of crude per barrel		10.574	$/bbl	
Feed per st. day of crude oil	FEEDD=	$31,469	$/day	
Working capital	WC=	$640,301		
Price of bacteria culture		10	$/m3	input
Number of employees at a time		2		input
Labor/(plant oper.-year)		$280,670		input
Total capital invest. cost	TCIC=	$1,918,145		
Sulfur removed (% of initial)		33.33%		input
Sulfur removed (% of crude wt)		1.00%		
Sulfur sale value		50.00	$/lt	input
Sulfur sale value		49.21	$/1000kg	
Sulfur in processed oil		2.00%	wt%	
Value of processed oil		12.598	$/bbl	
Weight of sulfer removed year		1249.0	ton/yr	
Crude type and date of cost		Resid Sep 93		
Crude cost intercept	A=	16.6455		input
Slope of cost [C = A + B*S]	B=	-2.0239905		input

Table 3-4 Summary of Operating Costs and Net Realization

Operating Costs		$/yr
Crude oil	FEEDA=	$10,384,761
Utilities	UT=	$20,491
Catalysts	CAT=	$936,889
Labor	LB=	$561,340
Maintenance	MT=	$38,363
Overhead, prop tax, insur.	[OH+PT+IN]=	$50,240
Capital charges	CC=	$383,629
Total Operating Costs	OC=	$12,375,713
Byproduct Credits		
Revenues from oil	OPC=	$12,372,609
Sulfur credit	BPC=	$61,469
Total Credits	CR=	$12,434,078
NET REALIZATION	NR=	$58,365
	NR/bbl=	$0.059

4

Economic Sensitivity Analysis

4.1 Introduction

This section describes the economic sensitivity analyses performed. As discussed in Section 3, the net realization per barrel is computed automatically with a Microsoft Excel spreadsheet. The effect of varying one or more input parameters permits an assessment of how sensitive the net realization is to changes in these parameters.

Three types of sensitivity analysis were performed for two feeds, Resid and Fuel Oil #6. The first type of analysis computes the effect of a ±10% change to the input parameters, one at a time, and shows which parameters the net realization is most sensitive to. The change is the direction that causes an increase in the net realization.

The second type of sensitivity analysis computes the net realization for a series of values of a particular input parameter. This computation is performed for several input parameters, one at a time. For Resid, the results are given in graphical and tabular forms, but for Fuel Oil #6 the results are shown only in tabular form.

The third type of sensitivity analysis computes the net realization with several key parameters simultaneously changed by 5%, in the direction that increases the net realization.

The input parameter values for the base case are shown in Table 2-2 (Resid with 3 wt% S is the feed for the base case). The other feed considered is Fuel Oil #6 with 2.8 wt% S. In this case, all input parameters are the same as the base case except the amount of sulfur and the cost curve constants, A and B.

As shown in Figure 2-1, the biochemical process has two distinct phases: 1) the biochemical batch process phase, which mixes the feed with the bacterial culture. Most of the sulfur is removed in this phase. 2) the product and waste-process phase, which separates the oil from the bacterial aqueous phase.

In the first phase, the feed and bacterial solution are forced to circulate through a motionless mixer by two pumps. The flow rate through the pumps are input parameters. Therefore, to examine the effect of increasing the feed amount per batch with all other parameters fixed, then either the amount of time for the mixing phase or the number of cycles that the total mass will circulate through the motionless mixer must be fixed. Except when stated otherwise, the amount of time for the first phase is fixed.

4.2 Effect of a 10% Change in the Input Parameters on the Net Realization

Table 4-1 shows the results of computing the net realization per barrel, NR/bbl, for the base case with a ±10% change in several input parameters, one at a time; the feed is Resid with 3.0 wt% S. The first column shows the name of the input parameter, the second column shows the base value. The third column shows the new value, which is 10% greater or smaller than the base value. The forth column shows the net realization per barrel when the corresponding parameter is changed to the new value. The last column shows the percentage increase in the NR/bbl. This percentage change is computed by the expression below.

$$\% \text{ Change NR/bbl} = \frac{NR_{new} - NR_{base}}{|NR_{base}|} \times 100 \qquad (4\text{-}1)$$

where NR_{base} is the net realization per barrel computed with the base values, NR_{new} is the net realization per barrel computed with the base values for all input parameters except the new value for the parameter in the corresponding row. The denominator of eqn. 4-1 is the absolute value of NR_{base}. This percentage change of NR/bbl is a measure of the sensitivity to the corresponding parameter.

The results are displayed in decreasing order of magnitude of the percentage change on the NR/bbl. Hence, variations in the parameters at the top of table have a larger effect on the net realization than those at the bottom. The plus sign on the value of the % Change NR/bbl indicates that the net realization increased.

From Table 4-1, we conclude that the most important parameters are the amount of sulfur in the feed, the slope of the curve "Feed Cost vs Sulfur Content," the fraction of sulfur removed, the volumetric ratio of bacterial culture to oil, the price of the bacterial culture, the price of bacterial culture, the total batch processing time, the amount of oil to be processed per batch, etc.

Section 4.3.5 shows that when the cost of feed, C, as a function of sulfur is given by a linear function $C = A + B^*S$, where A and B are constants and S is the wt% of sulfur, as shown in Section 2 for Resid, then by reducing the sulfur content of r, e.g. $r = 0.33$, the feed will increase its market value of $\Delta C = - r^*B^*S_i$, where S_i is the initial sulfur content. The intercept A and the slope B are set by the market, over which we have no control. Figure 2-12 shows the curve "Feed Cost vs Sulfur Content," for Resid.

The value of the % change on NR/bbl is sensitive to the NR/bbl for the base parameters. This can be understood by noticing that, in eqn. 4-1, the denominator is the NR/bbl for the base parameters. Therefore, if this value is close to zero, the resulting % change on NR/bbl becomes very large. Thus, with a different set of parameters, the same magnitudes of the % change NR/bbl values would not be expected. However, the order of the input parameters, when sorted by decreasing magnitude of % change in NR/bbl, and the relative magnitude of % change in NR/bbl should remain approximately the same.

Table 4-2 shows the sensitivity calculations when the feed is Fuel Oil #6 with 2.8 wt% S. Changing any single parameter by 10% was not enough to produce a positive NR/bbl. Also, the order of parameters remains approximately the same. The fact that the magnitude of the slope, B, of the curve "Feed Cost vs Sulfur Content," for Oil #6 is smaller decreases the net realization. If the slope were zero, i.e. a flat curve, the cost would be independent of sulfur content, and reducing sulfur would not be economically feasible, no matter how inexpensive the process was.

Figure 2-13 shows the curve "Feed Cost vs Sulfur Content," for Fuel Oil #6.

4.3 Effect of Varying Input Parameters on the Net Realization

This subsection describes the second type of sensitivity analysis performed. For each input parameter, the net realization per barrel is computed for a about five values. These calculations were performed for Resid and Fuel Oil #6.

4.3.1 Variation of Bacterial Cost on the Net Realization

Figure 4-1 shows the net realization per barrel as a function of the bacterial solution cost for Resid. As the bacterial cost decreases, the net realization increases linearly. When the variation is linear, coefficients A (intercept) and B (slope) are given, to facilitate the computation of the net realization at other intermediate input values. The slope indicates the variation in net realization for one unit of variation in the input parameter.

A similar calculation is performed for Fuel Oil #6. The results are in Table 4-3.

4.3.2 Variation of Volumetric Ratio Bacterial Culture to Oil on the Net Realization

Figure 4-2 shows the net realization per barrel for the base case as a function of the volumetric ratio of bacterial solution to oil, r_V. As the volumetric ratio decreases, the net realization increases linearly.

Table 4-4 shows the results for Fuel Oil #6.

4.3.3 Variation of Total Batch Time on the Net Realization

Figure 4-3 shows the net realization per barrel as a function of the total batch time. As the total batch time decreases the net realization increases linearly. This calculation assumes that the same sulfur reduction is achieved in a shorter time.

Table 4-5 shows the results for Fuel Oil #6.

4.3.4 Variation of Total Batch Time and Bacterial Cost on the Net Realization

Figure 4-4 shows the net realization per barrel as a function of the total batch time for several costs of the bacterial solution. For a given cost, as the total batch time decreases the net realization increases linearly. As the bacterial cost decreases, the curves are shifted upwards, increasing the net realization.

Table 4-6 shows the results for Fuel Oil #6.

4.3.5 Variation of Feed Sulfur Content on the Net Realization

Figure 4-5 shows the net realization per barrel as a function of the sulfur content of the feed. As the sulfur content increases, the net realization increases linearly. This finding makes sense since the process removes a fixed percentage of sulfur (33.33% for the base case), and the cost of the feed is linear with the amount of sulfur. To show this, let the cost of feed as a function of its sulfur content be

$$C = A + B^*S \qquad (4\text{-}2)$$

where A and B are constants (A is the intercept and B is the slope), S is the percentage of sulfur, and C is the cost per barrel. Let r be the fraction removed in the process, i.e. $r = 0.33$ for the base case. Let S_i be the initial sulfur content and S_f the final content. Therefore:

$$r = \frac{S_i - S_f}{S_i} \tag{4-3}$$

Let the cost of feed with S_i sulfur be C_i, and the cost of feed with S_f sulfur be C_f. Hence, from eqn. 4-2.

$$C_i = A + B^*S_i \tag{4-4}$$

and:

$$C_f = A + B^*S_f \tag{4-5}$$

The increase in value of the feed is $\Delta C = C_f - C_i$. From eqns. 4-4 and 4-5 it follows that:

$$\Delta C = B^*(S_f - S_i) \tag{4-6}$$

from eqns. 4-6 and 4-3:

$$\Delta C = - r^*B^*S_i \tag{4-7}$$

Therefore, from eqn. 4-7, the larger the content of sulfur in the feed, the larger is the price differential between feed and product.

Table 4-7 shows the results for Fuel Oil #6.

4.3.6 Variation of the Number of Operators on the Net Realization

Figure 4-6 shows the net realization per barrel as a function of the number of operators. As the number of operators decreases, the net realization increases. The base case is for 2 operators working all time, 24 hours per day. An operator can be employed part-time, which would explain the fractional value. A similar effect is found by varying of the operator's salary, instead of the number of operators.

Table 4-8 shows the results for Fuel Oil #6.

4.3.7 Variation of the Amount of Oil per Batch at Fixed Batch Time on the Net Realization

Figure 4-7 shows the net realization per barrel as a function of the amount of feed. As the amount of feed increases, the net realization increases. These calculations assume that the total time is fixed, even though the reactor container is larger as more feed is used, but it is assumed that the total time remains the same.

Table 4-9 shows the results for Fuel Oil #6.

4.3.8 Variation of the Amount of Oil per Batch at Fixed Number of Cycles on the Net Realization

Figure 4-8 shows the net realization per barrel as a function of the amount of feed. As the amount of feed increases, the net realization increases, reaches a maximum, and then decreases. These calculations assume that the number of batch cycles is fixed at 50 cycles. The reactor container is larger as more feed is used; hence, the total time increases as more feed is used, since the pumps flow rate is not changed. The variation in the net realization is very small.

Table 4-10 shows the results for Fuel Oil #6.

4.3.9 Variation of the Number of Cycles on the Net Realization

Figure 4-9 shows the net realization per barrel as a function of the number of cycles. As the latter decreases, the net realization increases, since less time and energy would be necessary.

Table 4-11 shows the results for Fuel Oil #6.

4.3.10 Variation of the Pumps Flow Rate on the Net Realization

Figure 4-10 shows the net realization per barrel as a function of the flow rate in pumps 1 and 2. A flow factor is used to indicate the variation in flow. The mass flow rate in pumps 1 and 2 are the base case values multiplied by the flow factor. As the flow factor increases, the net realization increases, since the total time is decreased. It is assumed, in this case, that a fixed number of cycles is necessary.

Table 4-12 shows the results for Fuel Oil #6.

4.3.11 Variation of the Slope of the Curve "Feed Cost vs Sulfur Content" on the Net Realization

Figure 4-11 shows the net realization per barrel as a function of the slope of the curve "Feed Cost vs Sulfur Content." The cost curve for Resid is shown in Figure 2-? The figure shows that the steeper the curve, i.e. the larger the magnitude of B, the larger the net realization.

Table 4-13 shows the results for Fuel Oil #6.

4.3.12 Variation of the Intercept of the Curve "Feed Cost vs Sulfur Content" on the Net Realization

Figure 4-12 shows the net realization per barrel as a function of the intercept value, A, of the curve "Feed Cost vs Sulfur Content." Changing the intercept shifts the cost curve up or down; this could reflect a variation in the cost of transportation, for example. The figure shows that as the intercept decreases, the net realization increases. The cost slope, B, is constant. Therefore, the differential cost is the same, i.e. ΔC is constant. But with smaller intercept the cost of feed is smaller.

Table 4-14 shows the results for Fuel Oil #6.

4.3.13 Variation of the Sulfur Reduction per Batch on the Net Realization

Figure 4-13 shows the net realization per barrel as a function of the reduction in sulfur per batch. As the reduction in sulfur increases, the net realization increases. As in all other calculations, all other parameters are assumed unchanged.

Table 4-15 shows the results for Fuel Oil #6.

4.3.14 Variation of the Flow Rate into the Centrifuge on the Net Realization

Figure 4-14 shows the net realization per barrel as a function of the flow rate into the centrifuge. As the flow rate increases, the time for the second phase, i.e. the separation phase, lessens. Consequently, the total time is decreased and the net realization increases. However, the effect is not very large.

Table 4-16 shows the results for Fuel Oil #6.

4.3.15 Variation of Pumps 1 and 2 Efficiency on the Net Realization

Figure 4-15 shows the net realization per barrel as a function of the efficiency of pumps 1 and 2. As the efficiency increases, less energy is wasted.

Consequently, the net realization increases. However, the effect is not very large.

Table 4-17 shows the results for Fuel Oil #6.

4.3.16 Effect of Variation of Sulfur in Feed on the Net Realization for Feeds from Different Sources and Delivered in Different Locations

Table 4-18 shows the net realization per barrel computed with the base case parameters, except for the type, price, and sulfur content of the feed. The feed prices were obtained from the September 13, 1993 issue of Bloomberg Oil Buyer's Guide.

The net realization per barrel is a linear function of the wt% of sulfur in the feed. Hence, the NR/BBL can be expressed as follows

$$NR/BBL = A + B^*(\%S/100) \qquad (4\text{-}8)$$

The constants A and B are shown for each case.

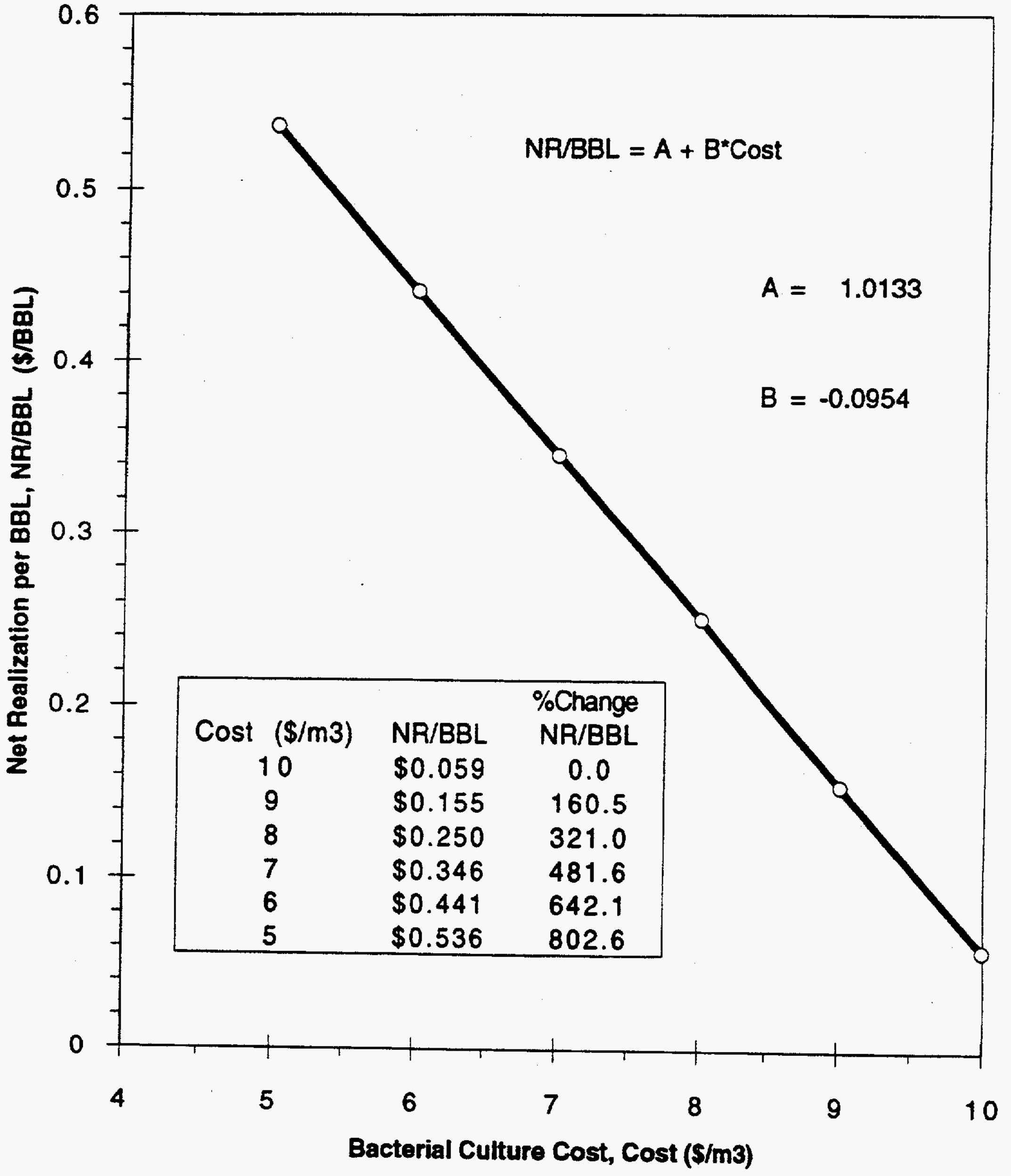
These constants are not the constants for the cost of the feed. The coefficients, also denoted A and B, for the price function, C = A + B*S, corresponding to the cases shown in Table 4-18, are given in Figures 2-14 to 2-19.

4.4 Effect of Simultaneously Varying by 5% of Several Key Parameters on the Net Realization

Table 4-19 shows the net realization per barrel as some key parameters are changed by 5% in the direction that causes the net realization to increase. The order of parameters is of decreasing effect on net realization, i.e. the first parameter has the largest effect. The effect is cumulative, i.e. the first row changes only the first parameter. The second row includes the change on the first parameter and the second one. At any row, the effect on the net realization is computed assuming that all parameters above are changed by 5%.

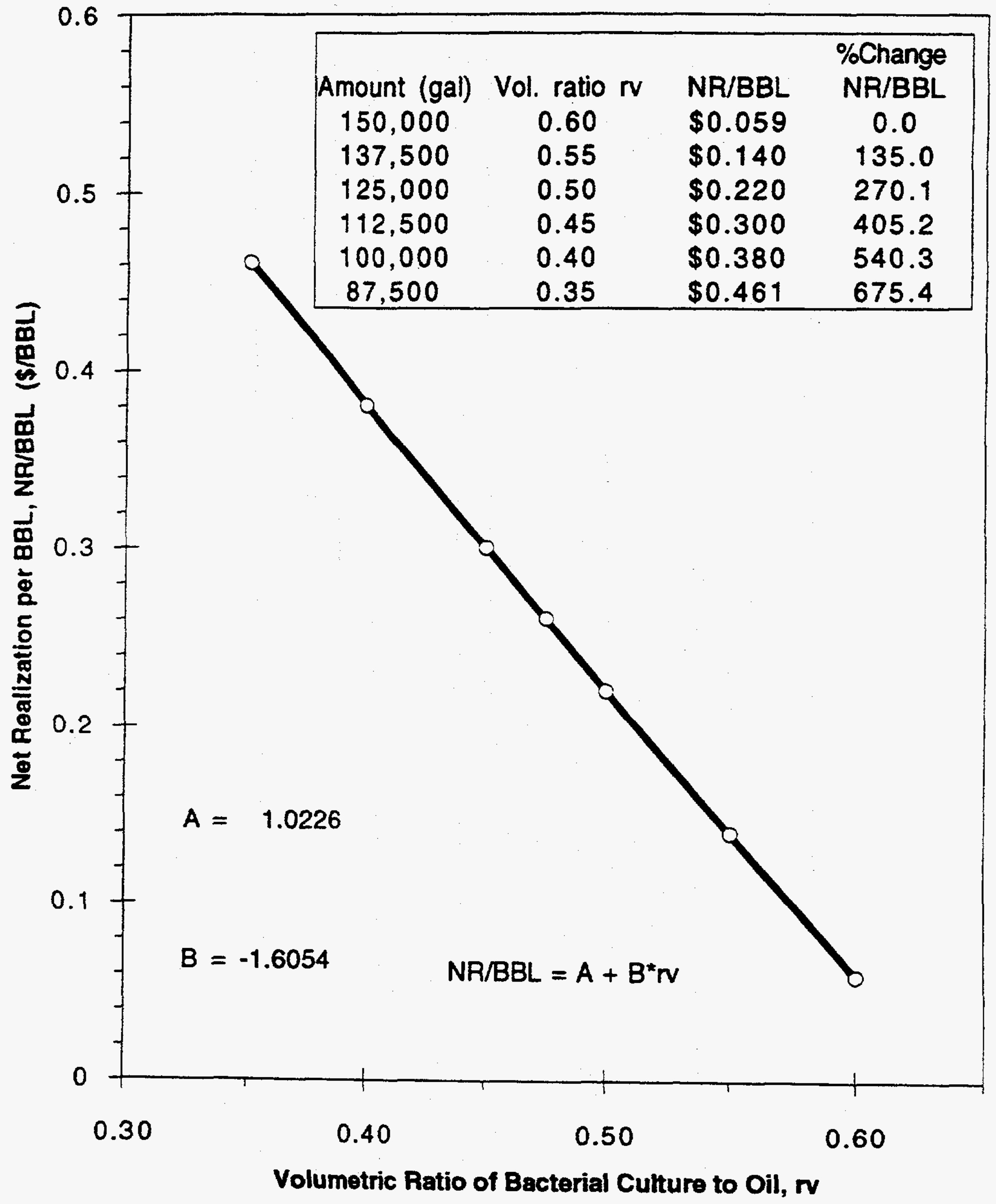
Table 4-20 shows the results for Fuel Oil #6.

**Figure 4.1 Effect of Variation of Bacterial Cost on Net Realization
(All Other Parameters at the Base Case Values)**



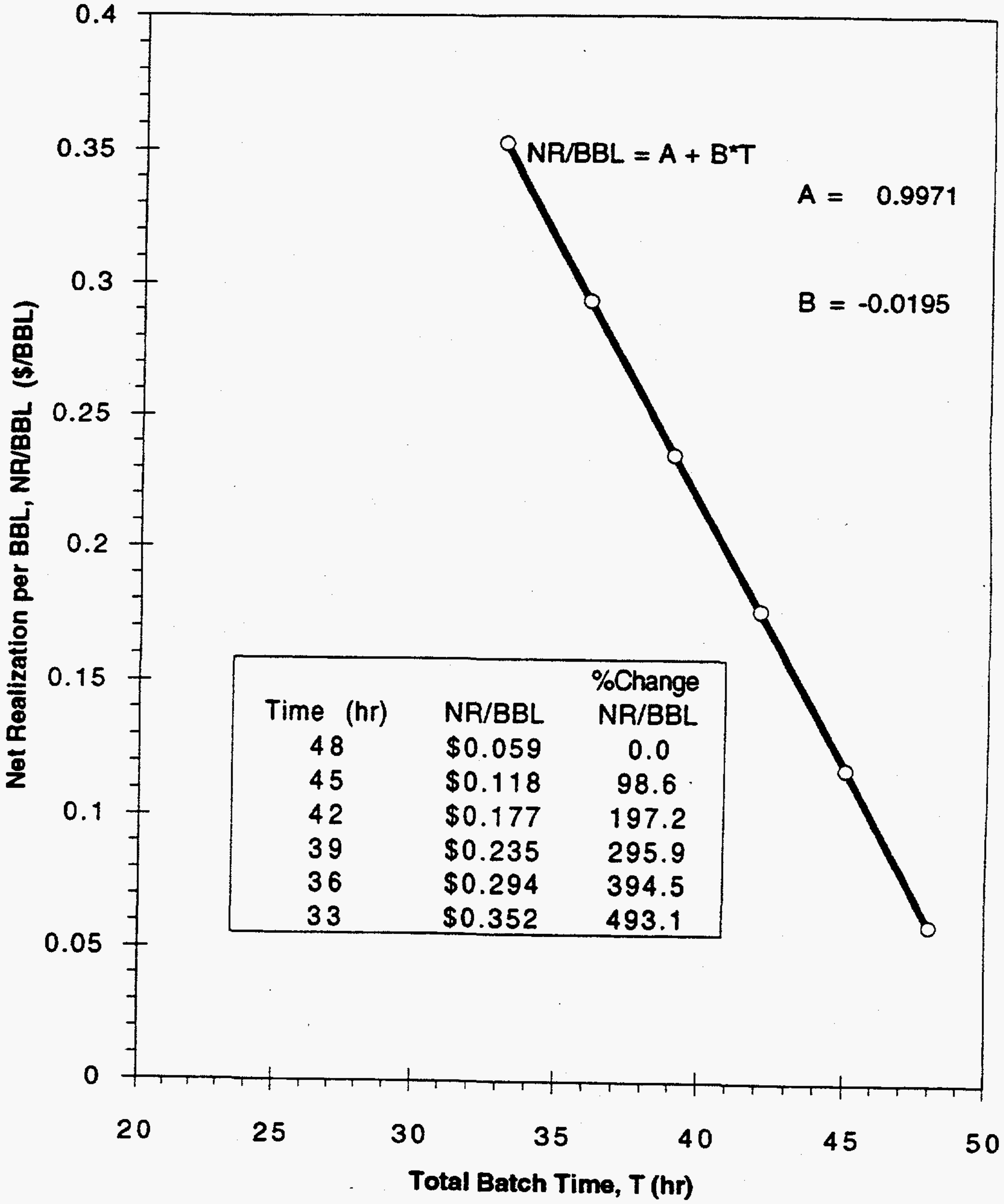
Cost ($/m3)	NR/BBL	%Change NR/BBL
10	$0.059	0.0
9	$0.155	160.5
8	$0.250	321.0
7	$0.346	481.6
6	$0.441	642.1
5	$0.536	802.6

Figure 4.2 Effect of Variation of Volumetric Ratio of Bacterial Culture to Oil on Net Realization (All Other Parameters at the Base Case Values)



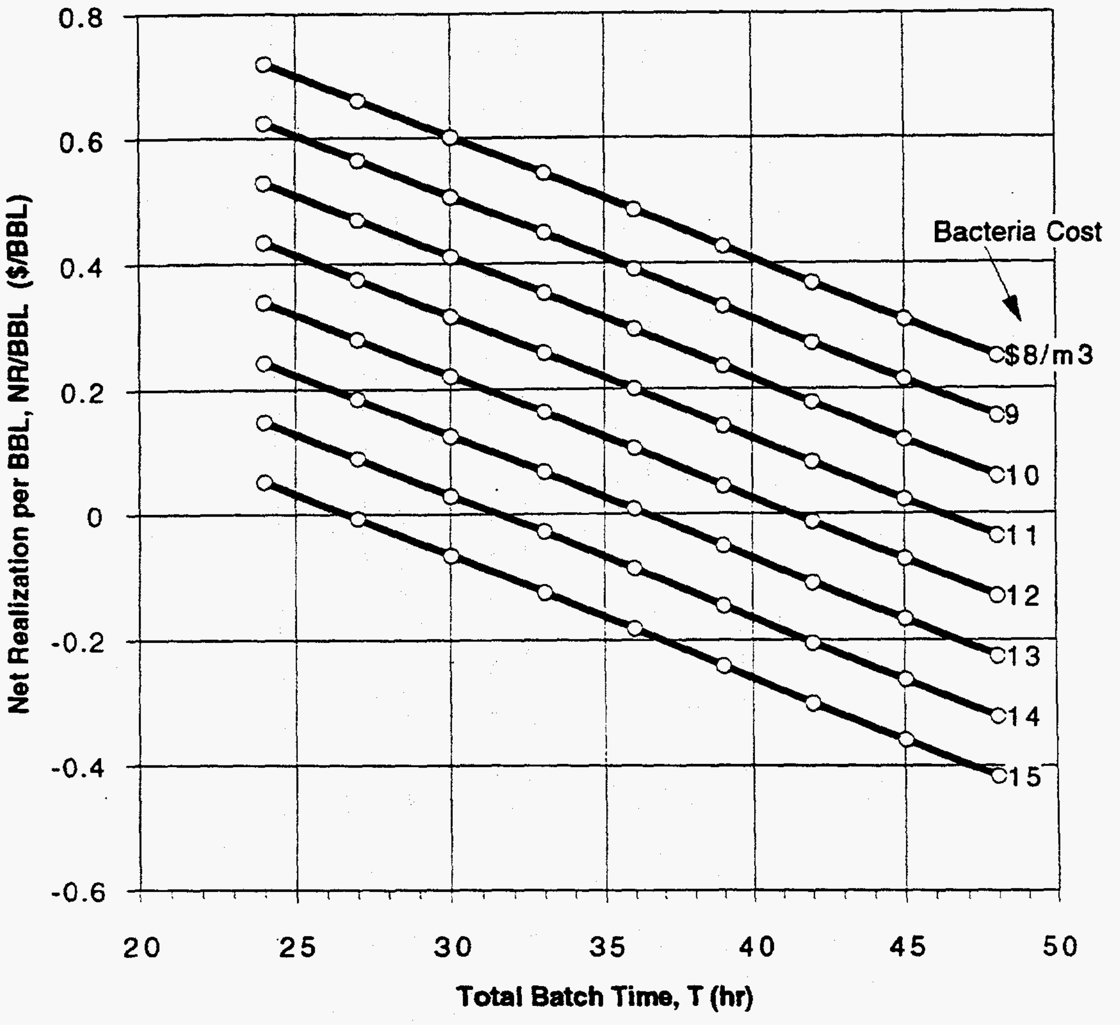
Amount (gal)	Vol. ratio rv	NR/BBL	%Change NR/BBL
150,000	0.60	$0.059	0.0
137,500	0.55	$0.140	135.0
125,000	0.50	$0.220	270.1
112,500	0.45	$0.300	405.2
100,000	0.40	$0.380	540.3
87,500	0.35	$0.461	675.4

Figure 4.3 Effect of Variation of Total Batch Time on Net Realization (All Other Parameters at the Base Case Values)



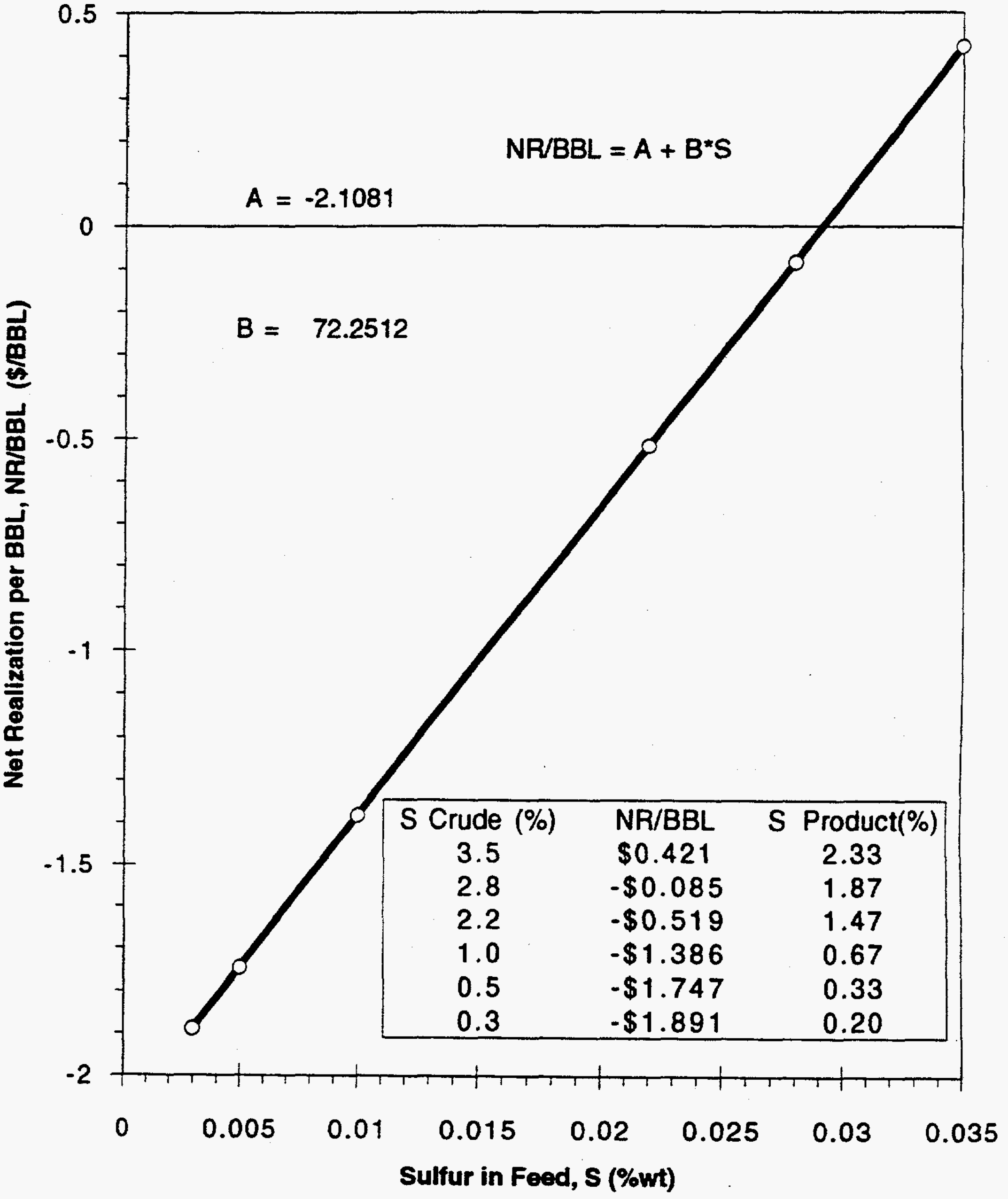
Time (hr)	NR/BBL	%Change NR/BBL
48	$0.059	0.0
45	$0.118	98.6
42	$0.177	197.2
39	$0.235	295.9
36	$0.294	394.5
33	$0.352	493.1

Figure 4.4 Effect of Variation of Total Batch Time and Bacterial Cost on Net Realization (All Other Parameters at the Base Case Values)



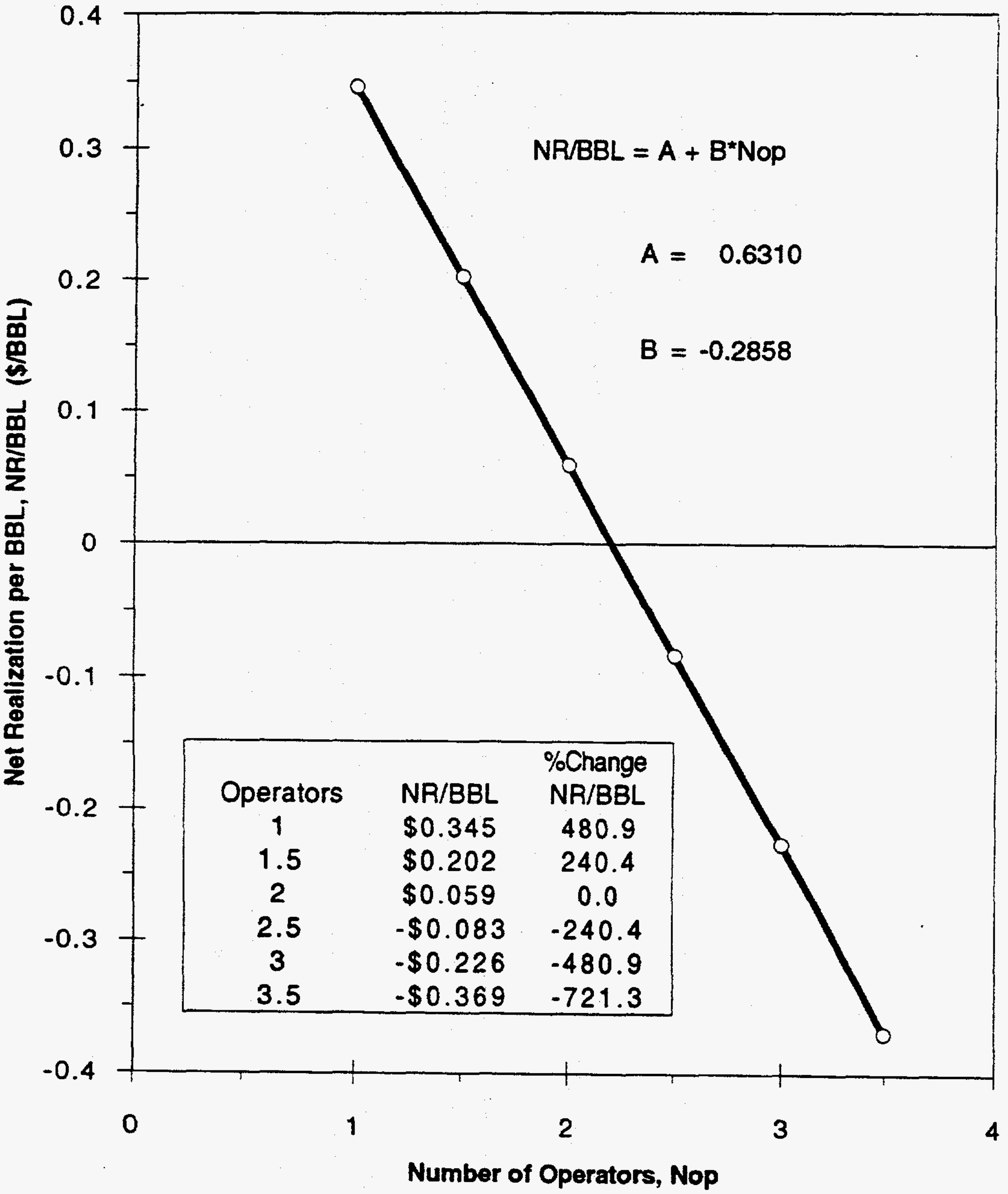
Bacteria Cost	Processing time (hr)								
($/m3)	48	45	42	39	36	33	30	27	24
8	$0.250	$0.309	$0.367	$0.426	$0.485	$0.543	$0.602	$0.660	$0.719
9	$0.155	$0.213	$0.272	$0.331	$0.389	$0.448	$0.506	$0.565	$0.624
10	$0.059	$0.118	$0.177	$0.235	$0.294	$0.352	$0.411	$0.470	$0.528
11	-$0.036	$0.023	$0.081	$0.140	$0.198	$0.257	$0.316	$0.374	$0.433
12	-$0.131	-$0.073	-$0.014	$0.044	$0.103	$0.162	$0.220	$0.279	$0.337
13	-$0.227	-$0.168	-$0.110	-$0.051	$0.008	$0.066	$0.125	$0.183	$0.242
14	-$0.322	-$0.264	-$0.205	-$0.146	-$0.088	-$0.029	$0.030	$0.088	$0.147
15	-$0.418	-$0.359	-$0.300	-$0.242	-$0.183	-$0.124	-$0.066	-$0.007	$0.051

Figure 4.5 Effect of Variation of Sulfur in Feed on Net Realization (All Other Parameters at the Base Case Values)



S Crude (%)	NR/BBL	S Product(%)
3.5	$0.421	2.33
2.8	-$0.085	1.87
2.2	-$0.519	1.47
1.0	-$1.386	0.67
0.5	-$1.747	0.33
0.3	-$1.891	0.20

Figure 4.6 Effect of Variation of Number of Operators on Net Realization (All Other Parameters at the Base Case Values)



Operators	NR/BBL	%Change NR/BBL
1	$0.345	480.9
1.5	$0.202	240.4
2	$0.059	0.0
2.5	-$0.083	-240.4
3	-$0.226	-480.9
3.5	-$0.369	-721.3

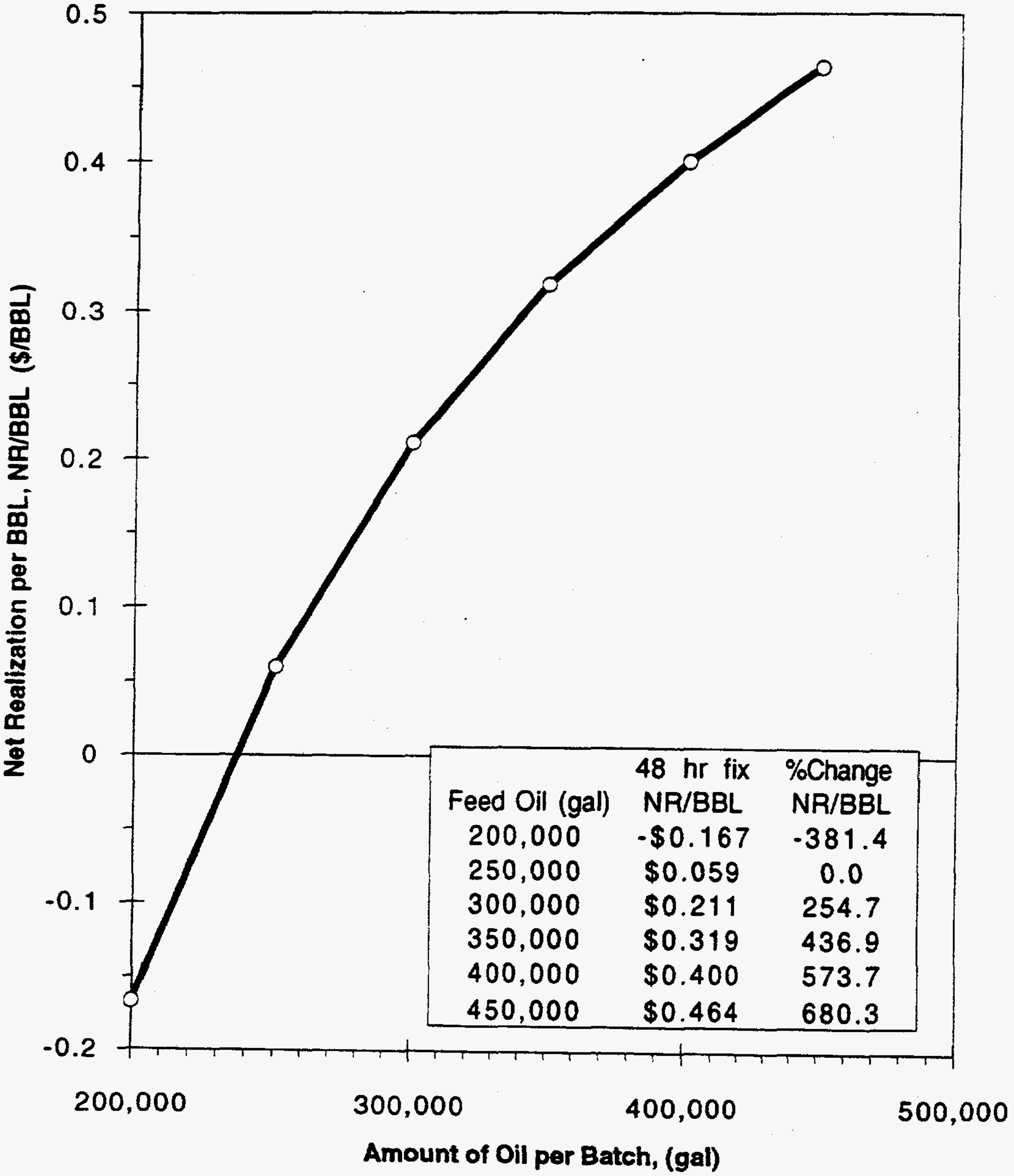
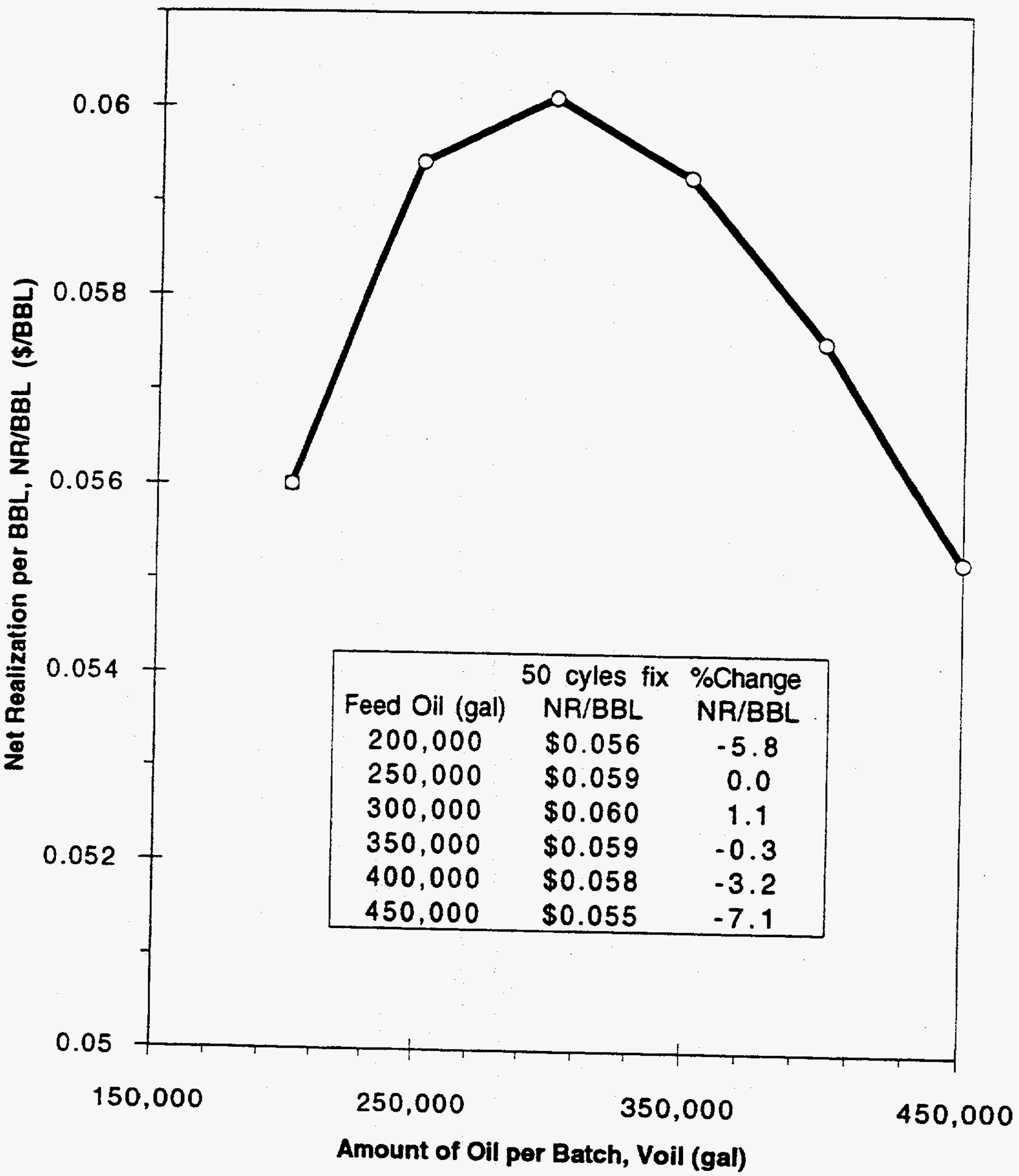


Figure 4.7 Effect of Variation of Amount of Oil per Batch at Fixed Batch Time = 48 hr on Net Realization (All Other Parameters at the Base Case Values)

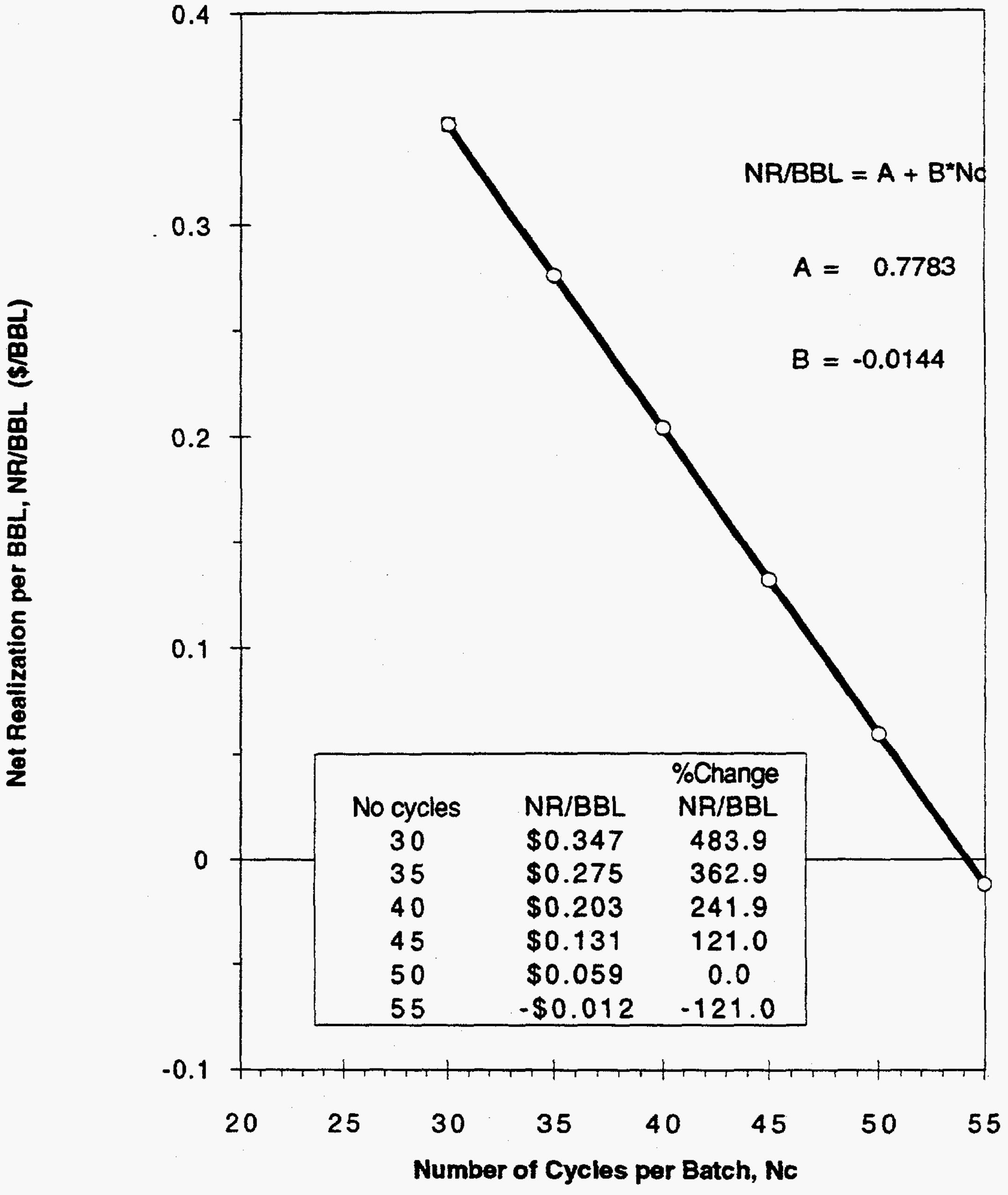
Feed Oil (gal)	48 hr fix NR/BBL	%Change NR/BBL
200,000	-$0.167	-381.4
250,000	$0.059	0.0
300,000	$0.211	254.7
350,000	$0.319	436.9
400,000	$0.400	573.7
450,000	$0.464	680.3

Figure 4.8 Effect of Variation of Amount of Oil per Batch at Fixed Batch Cycles = 50 on Net Realization (All Other Parameters at the Base Case Values)



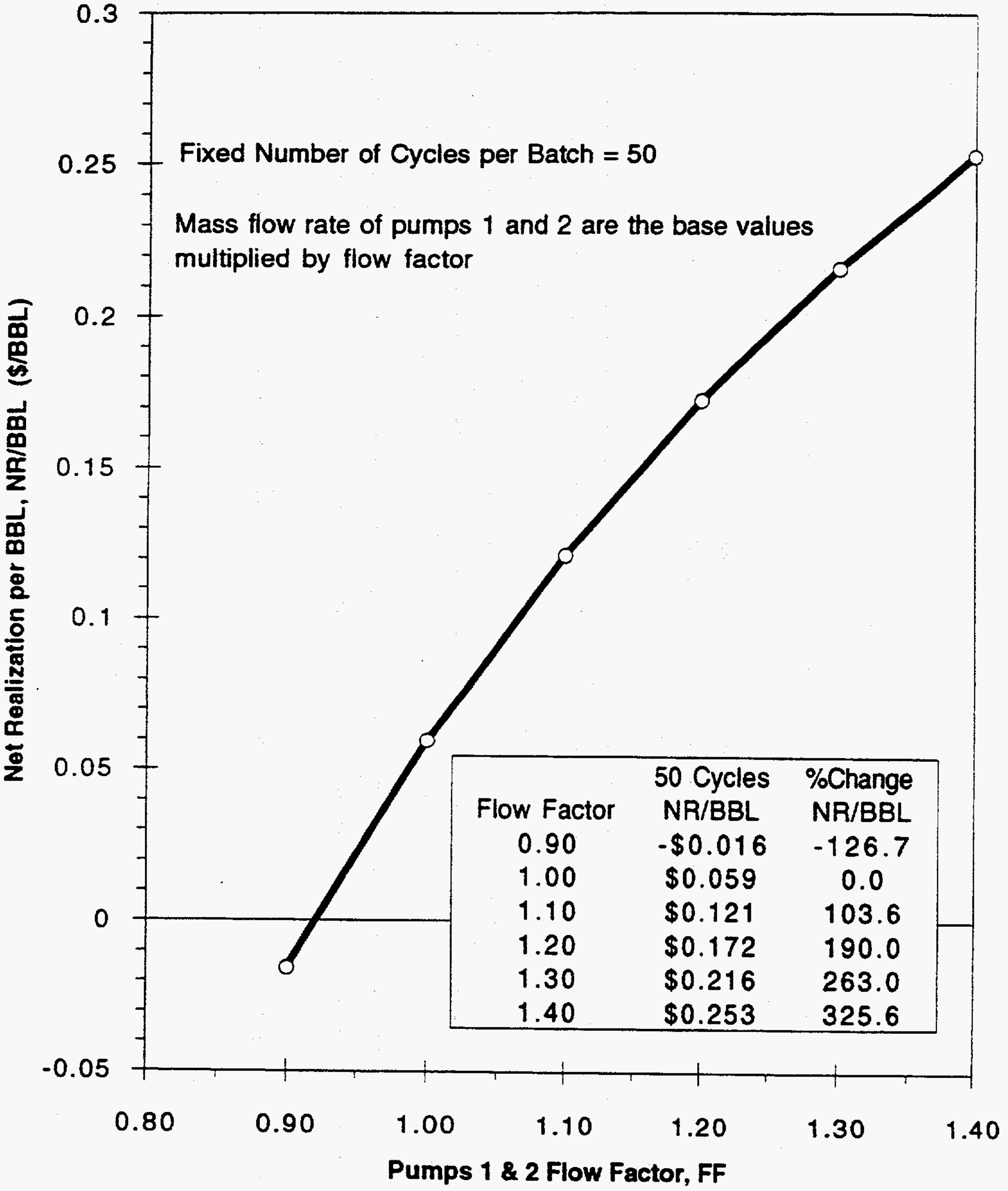
Feed Oil (gal)	50 cyles fix NR/BBL	%Change NR/BBL
200,000	$0.056	-5.8
250,000	$0.059	0.0
300,000	$0.060	1.1
350,000	$0.059	-0.3
400,000	$0.058	-3.2
450,000	$0.055	-7.1

Figure 4.9 Effect of Variation of Number of Cycles on Net Realization (All Other Parameters at the Base Case Values)



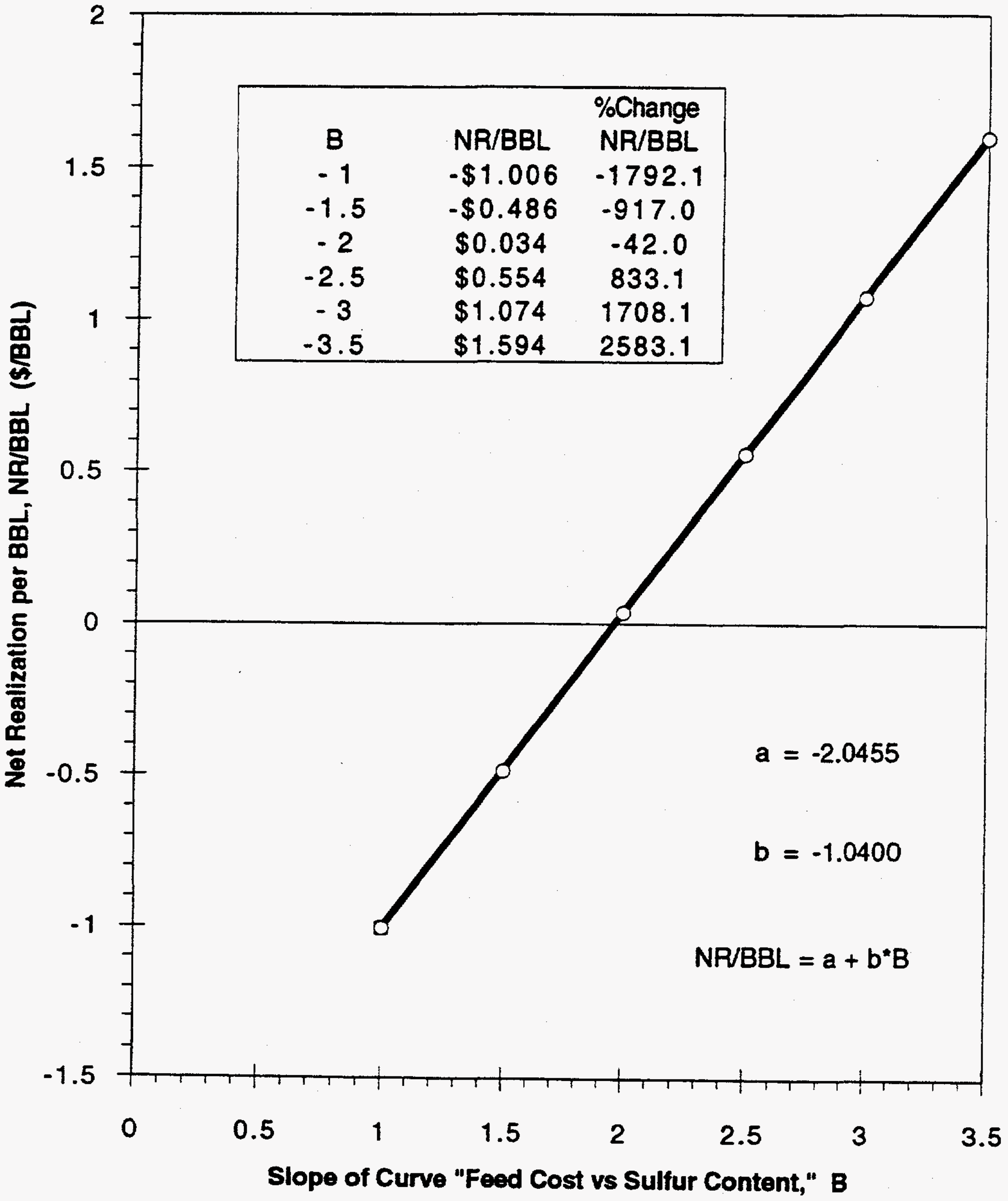
No cycles	NR/BBL	%Change NR/BBL
30	$0.347	483.9
35	$0.275	362.9
40	$0.203	241.9
45	$0.131	121.0
50	$0.059	0.0
55	-$0.012	-121.0

Figure 4.10 Effect of Variation of Flow Rate in Pumps No.1 & No.2 on Net Realization (All Other Parameters at the Base Case Values)



Flow Factor	50 Cycles NR/BBL	%Change NR/BBL
0.90	-$0.016	-126.7
1.00	$0.059	0.0
1.10	$0.121	103.6
1.20	$0.172	190.0
1.30	$0.216	263.0
1.40	$0.253	325.6

Figure 4.11 Effect of Variation of Slope of Curve "Feed Cost vs Sulfur Content" on Net Realization (All Other Parameters at the Base Case Values)



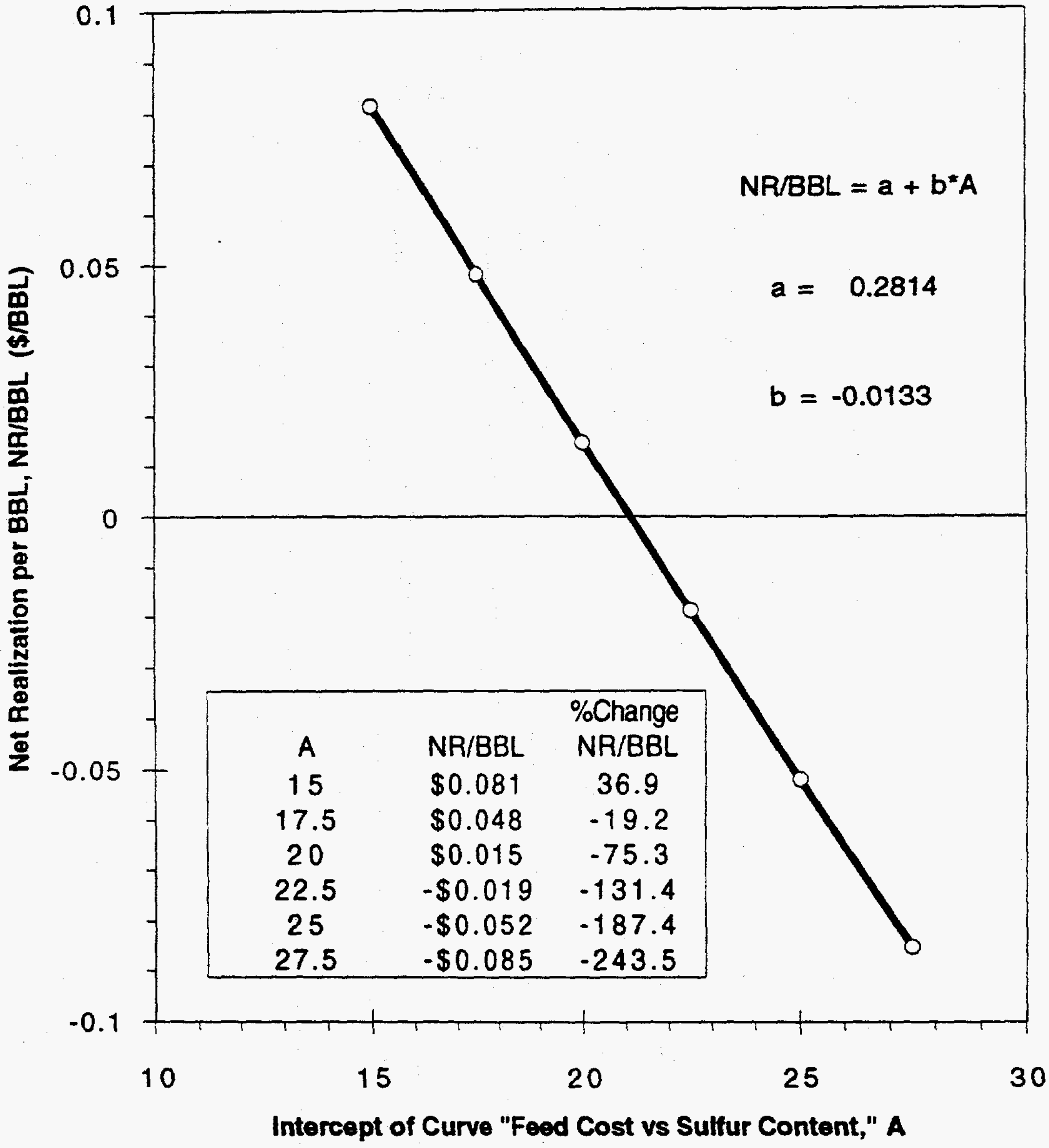
B	NR/BBL	%Change NR/BBL
- 1	-$1.006	-1792.1
-1.5	-$0.486	-917.0
- 2	$0.034	-42.0
-2.5	$0.554	833.1
- 3	$1.074	1708.1
-3.5	$1.594	2583.1

a = -2.0455

b = -1.0400

NR/BBL = a + b*B

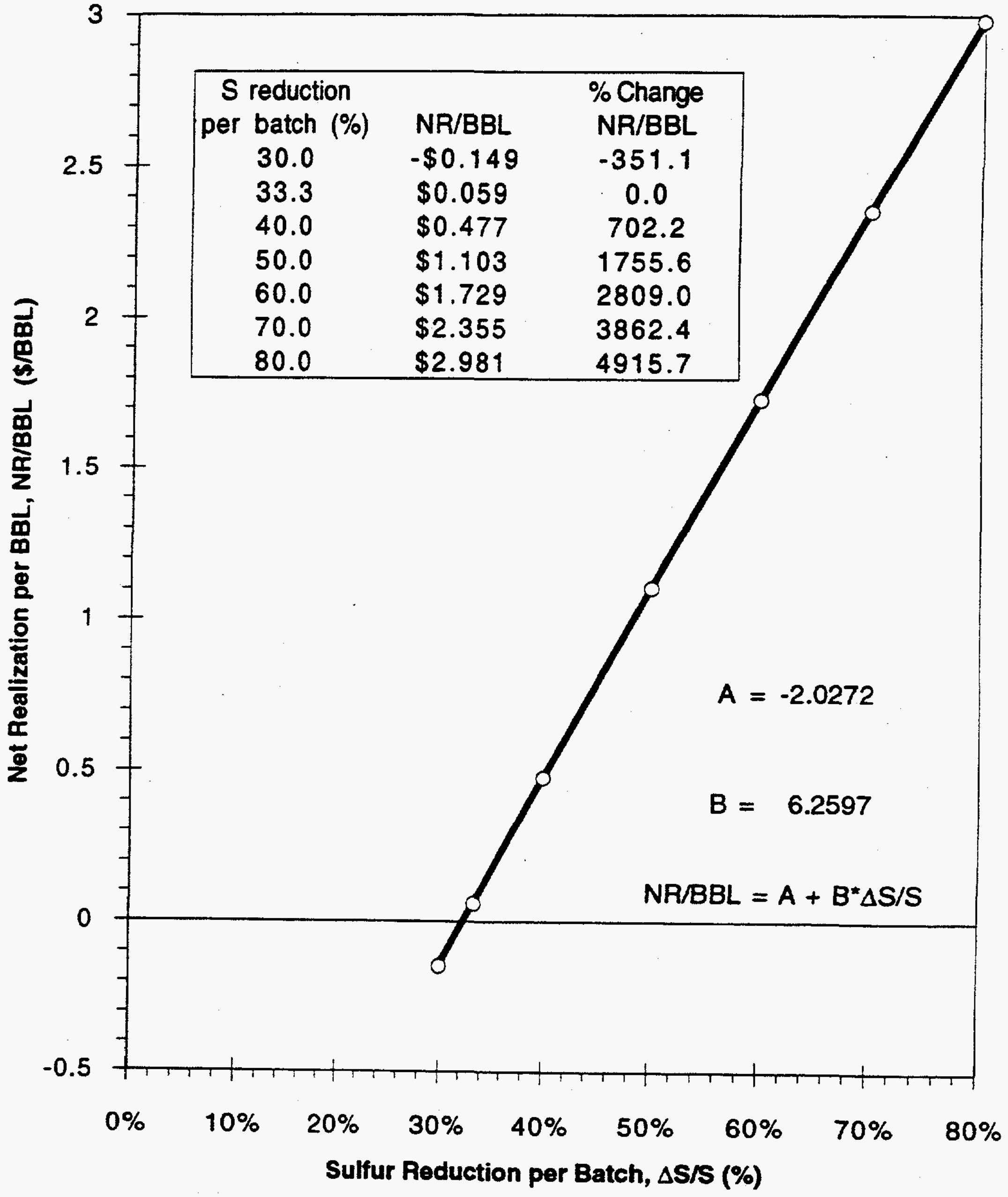
Figure 4.12 Effect of Variation of the Intercept* of Curve "Feed Cost vs Sulfur Content" on Net Realization (All Other Parameters at the Base Case Values)



A	NR/BBL	%Change NR/BBL
15	$0.081	36.9
17.5	$0.048	-19.2
20	$0.015	-75.3
22.5	-$0.019	-131.4
25	-$0.052	-187.4
27.5	-$0.085	-243.5

*Intercept is the y-value for x = 0 for a straight line curve (y = A + Bx). In this case the line is the curve that describes the cost of feed as a function of Sulfur content (Fig. 2-12).

Figure 4.13 Effect of Variation of Sulfur Reduction per Batch on Net Realization (All Other Parameters at the Base Case Values)



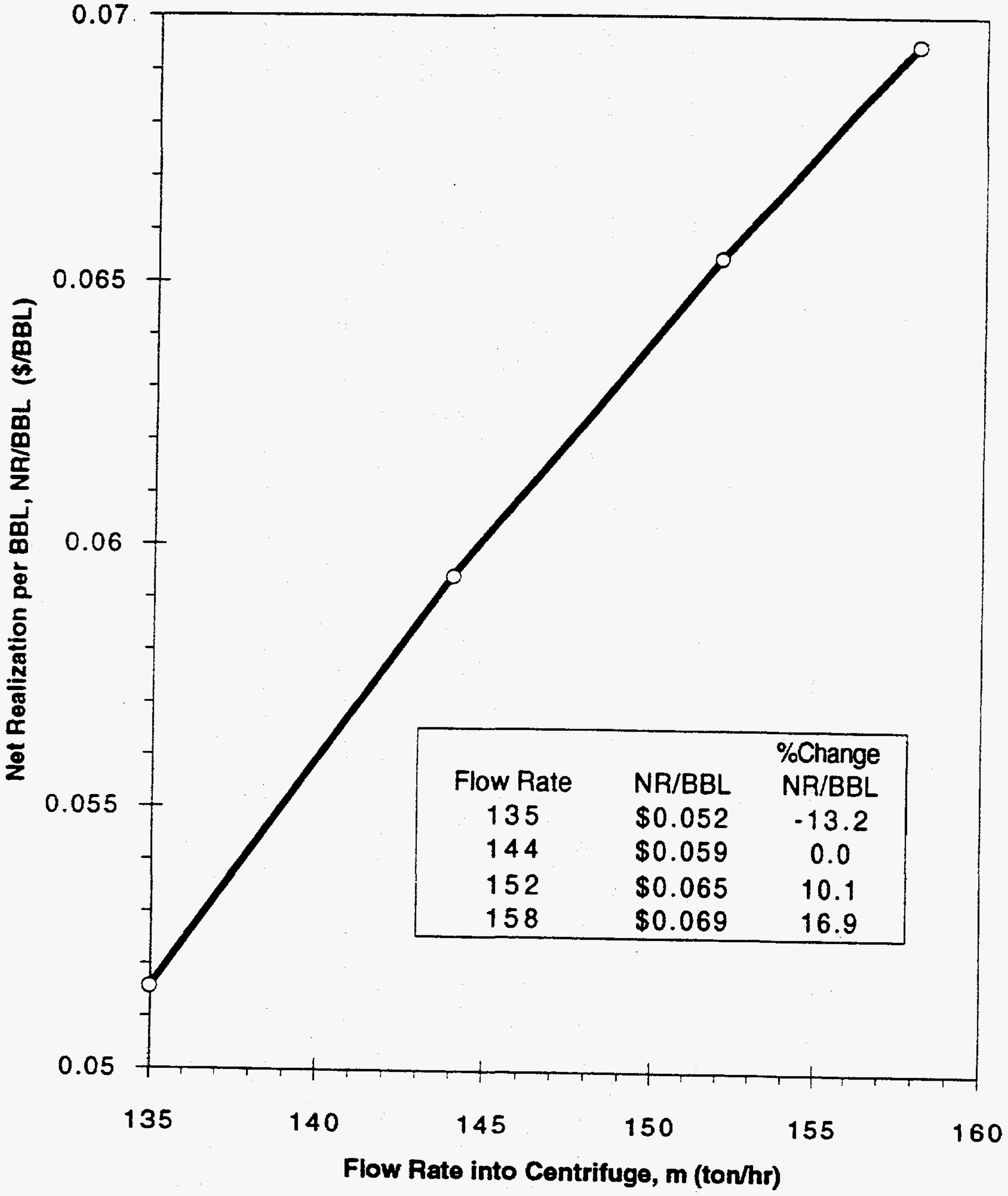
S reduction per batch (%)	NR/BBL	% Change NR/BBL
30.0	-$0.149	-351.1
33.3	$0.059	0.0
40.0	$0.477	702.2
50.0	$1.103	1755.6
60.0	$1.729	2809.0
70.0	$2.355	3862.4
80.0	$2.981	4915.7

$A = -2.0272$

$B = 6.2597$

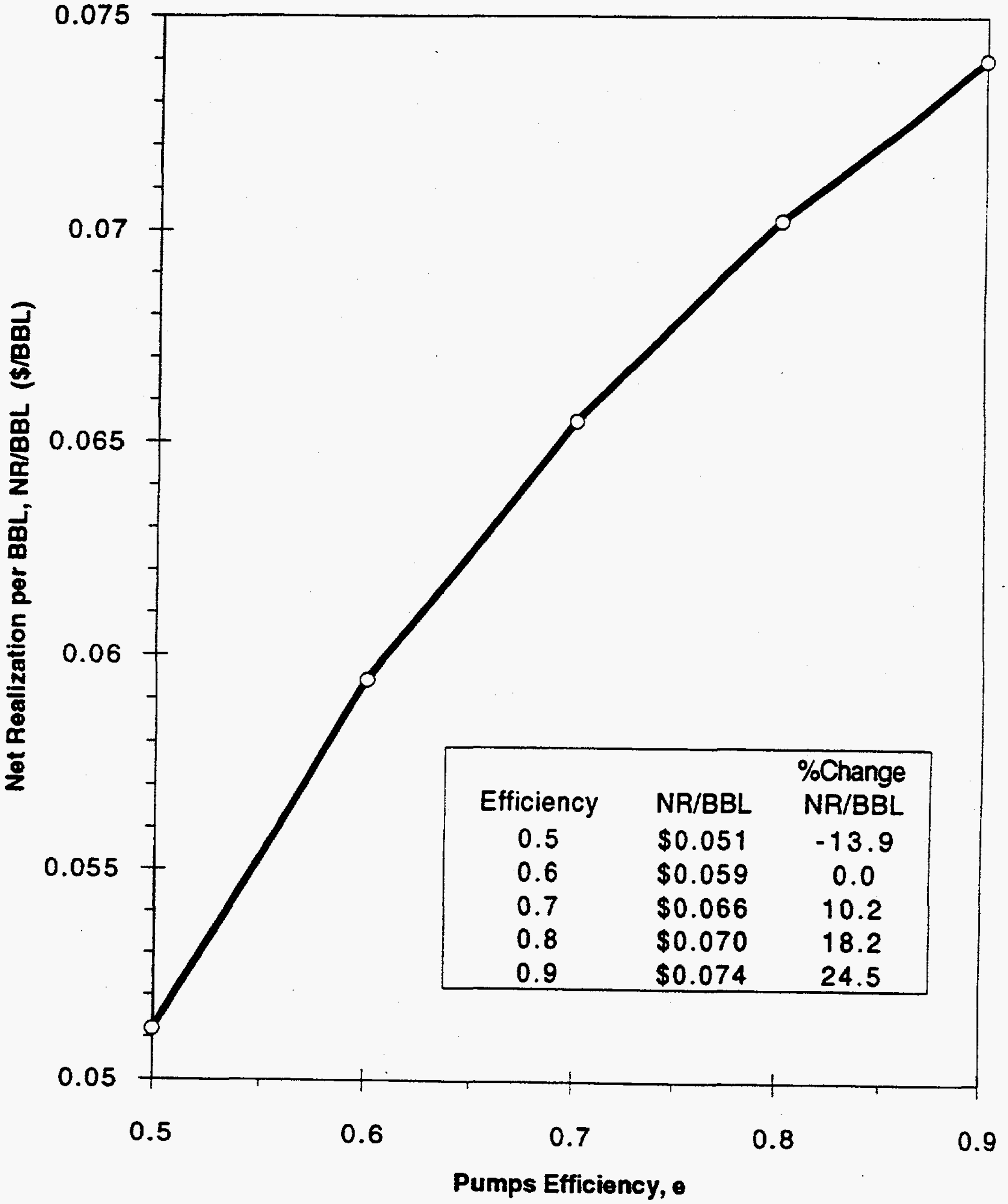
$NR/BBL = A + B^{*}\Delta S/S$

Figure 4.14 Effect of Variation of Flow Rate Into The Centrifuge on Net Realization (All Other Parameters at the Base Case Values)



Flow Rate	NR/BBL	%Change NR/BBL
135	$0.052	-13.2
144	$0.059	0.0
152	$0.065	10.1
158	$0.069	16.9

Figure 4.15 Effect of Variation of Pumps No.1 & No.2 Efficiency on Net Realization (All Other Parameters at the Base Case Values)



Efficiency	NR/BBL	%Change NR/BBL
0.5	$0.051	-13.9
0.6	$0.059	0.0
0.7	$0.066	10.2
0.8	$0.070	18.2
0.9	$0.074	24.5

Table 4-1 Effect of ±10% Change of Input Parameters on the Net Realization For Resid Fuel Oil, Sep. 93 (All Other Input Parameters are as in the Base Case)

Input Parameter	Base value	New Value	($) New NR/bbl	% Change NR/bbl
Sulfur in crude	3.00%	3.30%	0.276	+364.7
Crude cost slope (B)	-2.0240	-2.2264	0.270	+354.2
Sulfur removed (% of initial)	33.33%	36.67%	0.268	+351.1
Bacteria cult./oil feed vol. ratio (rv)	0.60	0.54	0.156	+162.1
Price of bacteria ($/m3)	$10.00	$9.00	0.155	+160.5
Batch processing time (hr)	48	43.2	0.153	+157.8
Oil to be treated (gal) (fixed time)	250,000	275,000	0.142	+138.9
Number of batch cycles	50	45	0.131	+121.0
Pump mass flow factor (fixed cycles)	1	1.1	0.121	+103.6
No. of employees at a time	2.0	1.8	0.117	+96.2
Stream days in a year	330	363	0.103	+72.6
Specific gravity of crude	0.80	0.88	0.071	+19.7
Solution flow rate into centrifuge	144	158.4	0.070	+17.3
Sulfur sale value ($/lt)	$50.00	$55.00	0.066	+10.5
Pump efficiencies	0.6	0.66	0.063	+6.5
Diameter of motionless mixer	0.5	0.45	0.063	+5.9
Electric. cost rate ($/kWh)	$0.05	$0.045	0.062	+4.6
Fraction of tank used	0.8	0.88	0.062	+4.5
Oil to be treated (gal) (fixed cycles)	250,000	275,000	0.060	+1.0

Table 4-2 Effect of 10% Increase of Input Parameters on the Net Realization For Fuel Oil #6, Sep. 93 (All other input parameters are as in the base case)

Input Parameter	Base value	New Value	($) New NR/bbl	% Change NR/bbl
Sulfur in crude	2.80%	3.08%	-0.627	+18.5
Sulfur removed (% of initial)	33.33%	36.67%	-0.633	+17.8
Crude cost slope (B)	-1.4072	-1.5479	-0.633	+17.7
Bacteria cult. vol. ratio (rv)	0.60	0.54	-0.673	+12.5
Price of bacteria ($/m3)	$10.00	$9.00	-0.674	+12.4
Batch processing time (hr)	48	43.2	-0.676	+12.2
Oil to be treated (gal) (fixed time)	250,000	275,000	-0.687	+10.7
Number of batch cycles	50	45	-0.698	+9.3
Pump mass flow factor (fix cycles)	1	1.1	-0.708	+8.0
No. of employees at a time	2.0	1.8	-0.713	+7.4
Stream days in a year	330	363	-0.716	+7.0
Specific gravity of crude	0.80	0.88	-0.758	+1.5
Solution flow rate into centrifuge	144	158.4	-0.759	+1.3
Sulfur sale value ($/lt)	$50.00	$55.00	-0.764	+0.8
Pump efficiencies	0.6	0.66	-0.766	+0.5
Diameter of motionless mixer	0.5	0.45	-0.766	+0.5
Electric. cost rate ($/kWh)	$0.05	$0.045	-0.767	+0.4
Fraction of tank used	0.8	0.88	-0.767	+0.3
Oil to be treated (gal) (fix cycles)	250,000	275,000	-0.769	+0.3

Table 4-3 Effect of Variation of Bacterial Culture Cost on NR (Fuel Oil #6, 2.8% S)

Bacterial Cost ($/m3)	NR/BBL	%Change NR/BBL
10	-$0.770	0.0
9	-$0.674	12.4
8	-$0.579	24.8
7	-$0.484	37.2
6	-$0.388	49.6
5	-$0.293	62.0

Table 4-4 Effect of Variation of Volumetric Ratio Bacterial Solution to Oil on Net Realization (Fuel Oil #6, 2.8% S)

Bacterial Amount (gal)	Volumetric Ratio rv	NR/BBL	%Change NR/BBL
150,000	0.60	-$0.770	0.0
137,500	0.55	-$0.689	10.4
125,000	0.50	-$0.609	20.9
112,500	0.45	-$0.529	31.3
100,000	0.40	-$0.449	41.7
87,500	0.35	-$0.368	52.1

Table 4-5 Effect of Variation of Total Batch Time on Net Realization (Fuel Oil #6, 2.8% S)

Time (hr)	NR/BBL	%Change NR/BBL
48	-$0.770	0.0
45	-$0.711	7.6
42	-$0.653	15.2
39	-$0.594	22.8
36	-$0.535	30.5
33	-$0.477	38.1

Table 4-6 Effect of Variation of Total Batch Time and Bacterial Culture Cost on Net Realization (Fuel Oil #6, 2.8% S)

Bacteria Cost $/m3	Processing time (hr)								
	48	45	42	39	36	33	30	27	24
8	-$0.579	-$0.520	-$0.462	-$0.403	-$0.345	-$0.286	-$0.227	-$0.169	-$0.110
9	-$0.674	-$0.616	-$0.557	-$0.499	-$0.440	-$0.381	-$0.323	-$0.264	-$0.205
10	-$0.770	-$0.711	-$0.653	-$0.594	-$0.535	-$0.477	-$0.418	-$0.359	-$0.301
11	-$0.865	-$0.807	-$0.748	-$0.689	-$0.631	-$0.572	-$0.513	-$0.455	-$0.396
12	-$0.961	-$0.902	-$0.843	-$0.785	-$0.726	-$0.667	-$0.609	-$0.550	-$0.492
13	-$1.056	-$0.997	-$0.939	-$0.880	-$0.821	-$0.763	-$0.704	-$0.646	-$0.587
14	-$1.151	-$1.093	-$1.034	-$0.975	-$0.917	-$0.858	-$0.800	-$0.741	-$0.682
15	-$1.247	-$1.188	-$1.129	-$1.071	-$1.012	-$0.954	-$0.895	-$0.836	-$0.778

Table 4-7 Effect of Variation of Sulfur in Feed on NR (Fuel Oil #6)

%S Feed	NR/BBL	%S Prod.
3.5	-$0.414	2.3
2.8	-$0.770	1.9
2.2	-$1.075	1.5
1.0	-$1.685	0.7
0.5	-$1.940	0.3
0.3	-$2.041	0.2

Table 4-8 Effect of Variation of Number of Operators on NR (Fuel Oil #6, 2.8% S)

No. of Operators	NR/BBL	%Change NR/BBL
1	($0.484)	37.1
1.5	-$0.627	18.6
2	-$0.770	0.0
2.5	-$0.913	-18.6
3	-$1.055	-37.1
3.5	-$1.198	-55.7

Table 4-9 Effect of Variation of Amount of Oil per Batch on NR at Fixed Batch Time

Feed Oil (gal)	48 hr fix NR/BBL	%Change NR/BBL
200,000	-$0.996	-29.4
250,000	-$0.770	0.0
300,000	-$0.618	19.7
350,000	-$0.510	33.7
400,000	-$0.429	44.3
450,000	-$0.365	52.5

Table 4-10 Effect of Variation of Amount of Oil per Batch on NR at Fixed Batch Cycles

Feed Oil (gal)	50 Cycles NR/BBL	%Change NR/BBL
200,000	-$0.773	-0.4
250,000	-$0.770	0.0
300,000	-$0.769	0.1
350,000	-$0.770	0.0
400,000	-$0.772	-0.2
450,000	-$0.774	-0.5

Table 4-11 Effect of Variation of Number of Cycles on NR (Fuel Oil #6, 2.8% S)

Number of Cycles	NR/BBL	%Change NR/BBL
30	-$0.482	37.4
35	-$0.554	28.0
40	-$0.626	18.7
45	-$0.698	9.3
50	-$0.770	0.0
55	-$0.842	-9.3

Table 4-12 Effect of Variation of Flow Rates in Pumps No.1 & No.2 on NR (Fuel Oil #6, 2.8% S)

Flow Factor	50 Cycles NR/BBL	%Change NR/BBL
0.90	-$0.845	-9.8
1.00	-$0.770	0.0
1.10	-$0.708	8.0
1.20	-$0.657	14.7
1.30	-$0.613	20.3
1.40	-$0.576	25.1

Mass flow rate in pumps 1 & 2 are base values multiplied by flow factor

Table 4-13 Effect of Variation of Slope of Curve "Feed Cost vs Sulfur Content"

B	NR/BBL	%Change NR/BBL
-1.00	-$1.165	-51.3
-1.50	-$0.680	11.7
-2.00	-$0.194	74.8
-2.50	$0.291	137.8
-3.00	$0.776	200.9
-3.50	$1.262	263.9

Table 4-14 Effect of Variation of the Intercept of Curve "Feed Cost vs Sulfur Content"

A	NR/BBL	%Change NR/BBL
15.00	-$0.662	14.0
17.50	-$0.695	9.7
20.00	-$0.729	5.4
22.50	-$0.762	1.0
25.00	-$0.795	-3.3
27.50	-$0.829	-7.6

Table 4-15 Effect of Variation of Sulfur Reduction per Batch on NR (Fuel Oil #6)

S reduction	-0.769716	%Change NR/BBL
30%	-$0.907	-17.8
33%	-$0.770	0.0
40%	-$0.495	35.6
50%	-$0.084	89.1
60%	$0.328	142.6
70%	$0.739	196.0
80%	$1.151	249.5

Table 4-16 Effect of Variation of Flow Rate into Centrifuge on NR

Feed Oil (gal)	NR/BBL	%Change NR/BBL
135.00	-$0.778	-1.0
144.00	-$0.770	0.0
152.00	-$0.764	0.8
158.00	-$0.760	1.3

Table 4-17 Effect of Variation of Pumps No.1 & No.2 Efficiency on NR

Efficiency	NR/BBL	%Change NR/BBL
0.50	-$0.778	-1.1
0.60	-$0.770	0.0
0.70	-$0.764	0.8
0.80	-$0.759	1.4
0.90	-$0.755	1.9

Table 4-18 Effect of Variation of Sulfur in Feed on Net Realization for Different Sources, Locations and Prices of Feed (All Other Parameters as in Base Case)

US East Coast Spot No.6 Oil Cargo Prices

Feed %wt S =	2.8%	2.2%	2.0%	1.0%	0.70%	0.50%
NR/BBL =	$0.185	-$0.307	-$0.471	-$1.292	-$1.538	-$1.702
B=	82.021					
A=	-2.112		NR/BBL = A + B*(%S/100)			

Petroleos de Venezuela Official FOB Postings #6 Residual Fuel Prices

Feed %wt S =	2.8%	2.2%	2.0%	1.0%	0.70%	0.50%
NR/BBL =	-$0.044	-$0.486	-$0.633	-$1.369	-$1.590	-$1.737
B=	73.595					
A=	-2.105		NR/BBL = A + B*(%S/100)			

Estimated New York Contract Oil No.6 Cargo Prices

Feed %wt S =	2.8%	2.2%	2.0%	1.0%	0.70%	0.50%
NR/BBL =	-$0.199	-$0.629	-$0.772	-$1.488	-$1.703	-$1.846
B=	71.609					
A=	-2.204		NR/BBL = A + B*(%S/100)			

Average Prices of US East Coast Residual Fuel Oil No. 6
Consumer Tankcar, FOB Supplier's Rack

Albany NY

Feed %wt S =	2.2%	2.0%	1.5%
NR/BBL =	-$0.495	-$0.644	-$1.018
B=	74.753		
A=	-2.139		NR/BBL = A + B*(%S/100)

Boston MA

Feed %wt S =	2.2%	2.0%	1.5%
NR/BBL =	-$0.471	-$1.011	-$1.397
B=	77.144		
A=	-2.168		NR/BBL = A + B*(%S/100)

Norfolk VA

Feed %wt S =	2.4%	2.1%	1.5%
NR/BBL =	-$0.450	-$0.661	-$1.082
B=	70.264		
A=	-2.136		NR/BBL = A + B*(%S/100)

Baltimore MD

Feed %wt S =	2.00%	1.50%	1.0%
NR/BBL =	-$0.508	-$0.920	-$1.333
B=	82.513		
A=	-2.158		NR/BBL = A + B*(%S/100)

Buffalo NY

Feed %wt S =	1.50%	1.30%	1.1%
NR/BBL =	$1.765	$1.224	$0.682
B=	270.753		
A=	-2.296		NR/BBL = A + B*(%S/100)

Table 4-18 (Continued) Effect of Variation of Sulfur in Feed on Net Realization for Different Sources, Locations and Prices of Feed (All Other Parameters as in Base Case)

	Northwest Europe Oil No.6 Cargo Prices			
Feed %wt S =	3.0%	2.5%	1.5%	
NR/BBL =	$0.336	-$0.068	-$0.876	
B=	80.854			
A=	-2.089			NR/BBL = A + B*(%S/100)
	US Coast Residual Fuel Oil No.4 **Consumer Tankcar, FOB Supplier's Rack Average Prices**			
	Boston MA			
Feed %wt S =	1.00%	0.75%		
NR/BBL =	-$1.229	-$1.477		
B=	99.153			
A=	-2.220			NR/BBL = A + B*(%S/100)
	New Haven CT			
Feed %wt S =	1.00%	0.50%		
NR/BBL =	-$0.643	-$1.446		
B=	160.562			
A=	-2.248			NR/BBL = A + B*(%S/100)

Table 4-19 Effect of Simultaneous ±5% Change in Key Parameters on the Net Realization for Resid Fuel Oil, Sep. 93
(All Other Input Parameters are as in the Base Case)

Input Parameter	Base value	New Value	Cummulative New NR $/bbl	Add. %Increase NR/bbl
Sulfur in feed	3.00%	3.15%	0.168	182.4
Sulfur removed (% of initial)	33.33%	35.00%	0.277	65.3
Bacteria cult./oil feed vol. ratio (rv)	0.60	0.57	0.325	17.4
Price of bacteria ($/m3)	$10.00	$9.50	0.371	13.9
Batch processing time (hr)	48	45.6	0.418	12.6
Oil to be treated (gal) (fixed time)	250,000	262,500	0.459	9.8
No. of employees at a time	2	1.9	0.485	5.6
Stream days in a year	330	346.5	0.505	4.3
Specific gravity of feed	0.80	0.84	0.511	1.2
Sulfur sale value ($/lt)	$50.00	$52.50	0.515	0.7
Pump efficiencies	0.6	0.63	0.517	0.3
Diameter of motionless mixer	0.5	0.475	0.518	0.3
Electric. cost rate ($/kWh)	$0.05	$0.0475	0.519	0.2
Fraction of tank used	0.8	0.84	0.521	0.2

Note: The Cummulative New Net Realization per barrel includes the change indicated in the corresponding row and all changes in the rows above. Therefore, the additional percentage increase in the NR is over and above the previous cummulative increase.

Table 4-20 Effect of Simultaneous ±5% Change in Key Parameters on the Net Realization for Fuel Oil #6, Sep. 93
(All Other Input Parameters are as in the Base Case)

Input Parameter	Base value	New Value	Cummulative New NR $/bbl	Add %Change NR/bbl
Sulfur in feed	2.80%	2.94%	-0.699	+9.3
Sulfur removed (% of initial)	33.33%	35.00%	-0.626	+10.3
Bacteria cult. vol. ratio (rv)	0.60	0.57	-0.578	+7.7
Price of bacteria ($/m3)	$10.00	$9.50	-0.533	+7.8
Batch processing time (hr)	48	45.6	-0.486	+8.8
Oil to be treated (gal) (fixed time)	250,000	262,500	-0.445	+8.4
No. of employees at a time	2.0	1.9	-0.419	+5.8
Stream days in a year	330	346.5	-0.393	+6.3
Specific gravity of feed	0.80	0.84	-0.387	+1.4
Sulfur sale value ($/lt)	$50.00	$52.50	-0.384	+0.9
Pump efficiencies	0.6	0.63	-0.382	+0.4
Diameter of motionless mixer	0.5	0.475	-0.381	+0.4
Electric. cost rate ($/kWh)	$0.05	$0.0475	-0.379	+0.3
Fraction of tank used	0.8	0.84	-0.378	+0.3

5

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5.1 Costing and Estimating of Process Equipment, Buildings and Structures for Chemical and Petrochemical Plants (In Chronological Order)

5.1.1 Books

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Appendix A

Least Squares Method for Curve Fitting

This appendix describes the Least Squares method for curve fitting used throughout to compute the coefficients A and B, of the linear equation below.

$$y = A + Bx \qquad \text{(A-1)}$$

The coefficients are computed in such way that the straight line given by eqn. A-1 best fit a set of data points with coordinates (x_i, y_i), where i = 1, 2, ... n. The straight line given by eqn. A-1 does not necessary pass through all points, i.e. y_i is not necessary equal to $A + Bx_i$. This difference usually is called the residual. Therefore, the residual for point i is given by:

$$\varepsilon_i = y_i - A - Bx_i \qquad \text{(A-2)}$$

The Least Squares method computes the coefficients A and B by minimizing the sum of the squares of the residuals. Let Z be the sum of squared residuals. Hence:

$$Z = \sum_{i=1}^{n} [y_i - A - Bx_i]^2 \qquad \text{(A-3)}$$

The partial derivatives of Z with respect to A and B are equated to zero in other to find the coefficients that produce the minimum of Z:

$$\frac{\partial Z}{\partial B} = \sum_{i=1}^{n} -2x_i[y_i - A - Bx_i] = 0 \qquad \text{(A-4)}$$

$$\frac{\partial Z}{\partial A} = \sum_{i=1}^{n} -2[y_i - A - Bx_i] = 0 \qquad \text{(A-5)}$$

Eqns. A-4 and A-5 form a system of 2 equations with 2 unknowns, shown below.

$$(\Sigma x_i)A + (\Sigma x_i^2)B = \Sigma x_i y_i \qquad \text{(A-6)}$$

$$nA + (\Sigma x_i)B = \Sigma y_i \qquad \text{(A-7)}$$

The solution of the system above is:

$$B = \frac{(\Sigma x_i)(\Sigma y_i) - n(\Sigma x_i y_i)}{(\Sigma x_i)^2 - n(\Sigma x_i^2)} \qquad \text{(A-8)}$$

$$A = \frac{(\Sigma x_i)(\Sigma x_i y_i) - (\Sigma x_i^2)(\Sigma y_i)}{(\Sigma x_i)^2 - n(\Sigma x_i^2)} \qquad \text{(A-9)}$$

Next, a numerical example is used to illustrate the calculations by the Least Squares method. Let the coordinates (x_i, y_i) be those in the table below:

i	x_i	y_i	$x_i{*}y_i$	x_i^2
1	5	33.17	165.8	25
2	7.5	26.02	195.2	56.25
3	10	20.29	202.9	100
4	12.5	17.71	221.3	156.25
5	15	11.63	174.5	225
$n = 5$	$\Sigma x_i = 50$	$\Sigma y_i = 108.82$	$\Sigma x_i y_i = 959.76$	$\Sigma x_i^2 = 562.5$

Therefore, using eqns. A-8 and A-9, it follows:

$$B = \frac{50 \times 108.82 - 5 \times 959.76}{50^2 - 5 \times 562.5} = -2.055 \qquad \text{(A-10)}$$

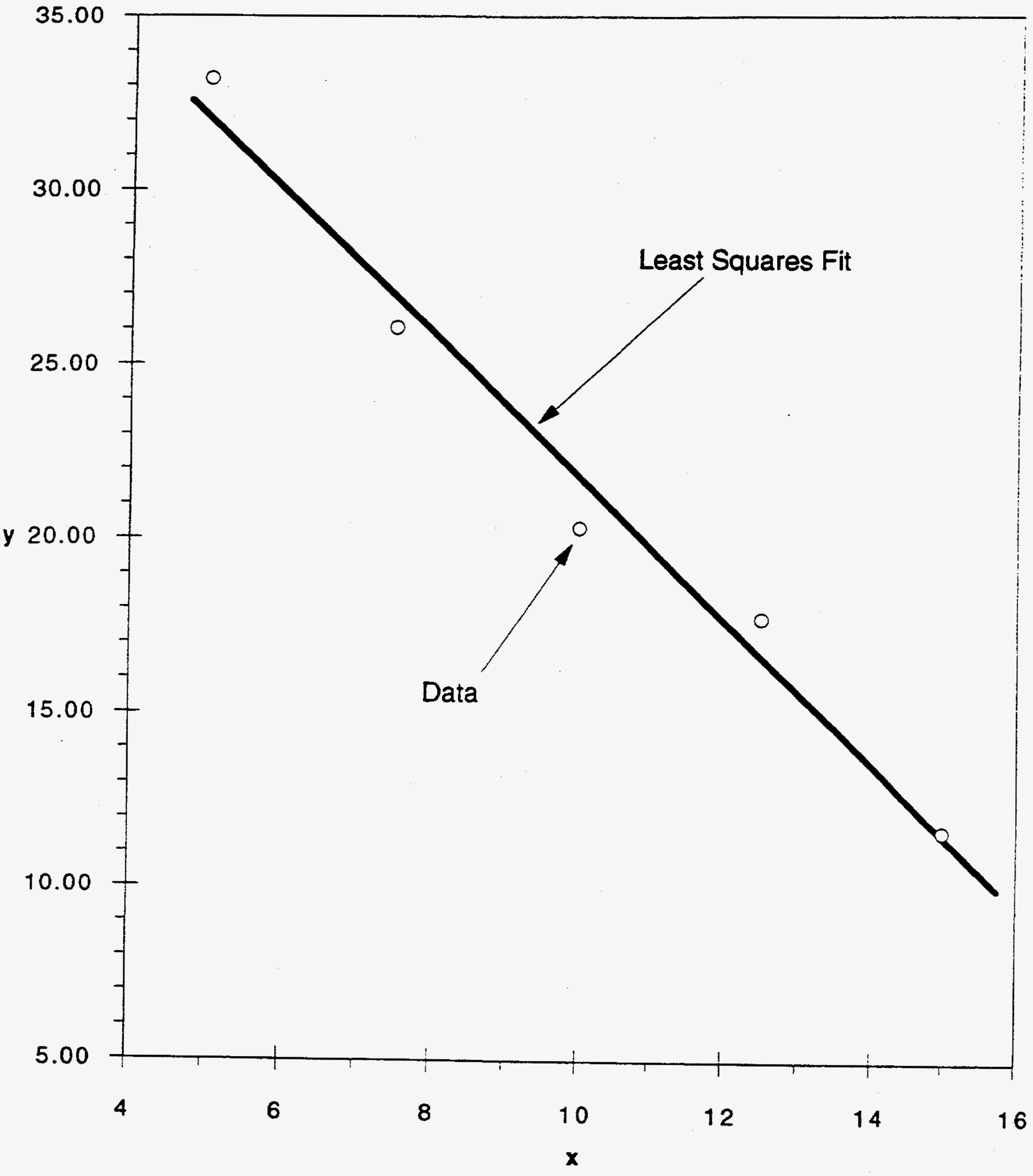
and

$$A = \frac{50 \times 959.76 - 562.5 \times 108.82}{50^2 - 5 \times 562.5} = 42.31 \qquad \text{(A-11)}$$

The above procedure is automatically computed by MS EXCEL through the function LINEST.

Figure A-1 shows the above data and the fitted line.

Figure A-1 Illustration of Least Squares Fit to a Data Set



APPENDIX B

CUMULATIVE LIST OF ALL PUBLICATIONS, REPORTS, AND PRESENTATIONS DEALING WITH BIOCHEMICAL TREATMENT OF FOSSIL FUELS

Publications, Reports, and Presentations

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