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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Participating Team

and

Acknowledgments


I would also like to acknowledge 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 biotechnical 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 from 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. Clostridium 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


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

Patents


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 on microbial species used and the chemical composition of the oil.

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


Appendix B

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

ECONOMIC FEASIBILITY OF BIOCHEMICALLY UPGRADED 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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Effect of Variation of Total Batch Time and Bacterial Cost on Net Realization (All Other Parameters at the Base Case Values)
Figure

4-5 Effect of Variation of Sulfur in Feed on Net Realization (All Other Parameters at the Base Case Values)

4-6 Effect of Variation of Number of Operators on Net Realization (All Other Parameters at the Base Case Values)

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)

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4-9 Effect of Variation of Number of Cycles on Net Realization (All Other Parameters at the Base Case Values)

4-10 Effect of Variation of Flow Rate in Pumps #1 & #2 on Net Realization (All Other Parameters at the Base Case Values)

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)

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)

4-13 Effect of Variation of Sulfur Reduction per Batch on Net Realization (All Other Parameters at the Base Case Values)

4-14 Effect of Variation of Flow Rate Into the Centrifuge on Net Realization (All Other Parameters at the Base Case Values)

4-15 Effect of Variation of Pumps #1 & #2 Efficiency on Net Realization (All Other Parameters at the Base Case Values)

A-1 Illustration of Least Squares Fit to a Data Set
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Surface Area of Filter Press or Intercept of Linear Eqn. ( y = A + Bx )</td>
</tr>
<tr>
<td>AH</td>
<td>Arabian Heavy</td>
</tr>
<tr>
<td>AHVR</td>
<td>Arabian Heavy Vacuum Residue</td>
</tr>
<tr>
<td>AIR</td>
<td>Additional Investment Requirements</td>
</tr>
<tr>
<td>AL</td>
<td>Arabian Light</td>
</tr>
<tr>
<td>ANS</td>
<td>Alaskan North Slope</td>
</tr>
<tr>
<td>AP</td>
<td>Aqueous Phase Processed Through the Precipitation Drum/Batch</td>
</tr>
<tr>
<td>APFR</td>
<td>Aqueous Phase Flow Rate Into Precipitation Drum</td>
</tr>
<tr>
<td>ASPH</td>
<td>Asphaltenes ($/yr)</td>
</tr>
<tr>
<td>ASPH(_u)</td>
<td>Unit Cost of Asphaltenes ($/bbl)</td>
</tr>
<tr>
<td>B</td>
<td>Slope of Linear Equation ( y = A + Bx )</td>
</tr>
<tr>
<td>( B_{0-10(V)} )</td>
<td>&quot;Bullet 0-10 barg&quot; Empirical Functional Relationship of Purchased Equipment Cost, ( C_P ), to Volume, ( V )</td>
</tr>
<tr>
<td>BC</td>
<td>Bacterial Culture/batch</td>
</tr>
<tr>
<td>BF</td>
<td>Bioreactor Fluids/batch</td>
</tr>
<tr>
<td>BFW</td>
<td>Boiler Feed Water cost per year</td>
</tr>
<tr>
<td>BFW(_u)</td>
<td>Unit Cost of Boiler Feed Water ($/Mgal)</td>
</tr>
<tr>
<td>BLE</td>
<td>Battery Limit Process Equipment Costs</td>
</tr>
<tr>
<td>BPC</td>
<td>By-Product Credits</td>
</tr>
<tr>
<td>BPT</td>
<td>Bioreactor Processing Time</td>
</tr>
<tr>
<td>BPY</td>
<td>Number of Process Batches Per Year</td>
</tr>
<tr>
<td>BTPT</td>
<td>Batch Total Processing Time</td>
</tr>
<tr>
<td>C</td>
<td>Cost of New York Cargo Resid Fuel Oil Per Barrel</td>
</tr>
<tr>
<td>( C_{ABM} )</td>
<td>Purchased Cost (1993) of Precipitation Drum Agitator</td>
</tr>
<tr>
<td>CAT</td>
<td>Catalysts</td>
</tr>
<tr>
<td>CATHC</td>
<td>Cat Canyon (California Heavy) Crude Oil</td>
</tr>
<tr>
<td>( C_{BM} )</td>
<td>Bare Module Equipment Cost</td>
</tr>
<tr>
<td>CC</td>
<td>Annual Capital Charges</td>
</tr>
<tr>
<td>CPB</td>
<td>FYPBBT</td>
</tr>
<tr>
<td>CCL</td>
<td>Canadian Cold Lake Crude Oil</td>
</tr>
<tr>
<td>CDHT</td>
<td>Catalysts for Distillate Hydrotreating</td>
</tr>
<tr>
<td>CEAI</td>
<td>Chemical Engineering Plant Cost Annual Index</td>
</tr>
<tr>
<td>CHM</td>
<td>Catalysts for Hydrogen Manufacture</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Purchased Equipment Cost</td>
</tr>
<tr>
<td>( CP(p_i) )</td>
<td>&quot;Centrifugal Pump&quot; Empirical Functional Relationship of ( F_P ) to ( p_i )</td>
</tr>
</tbody>
</table>
CP($w_s$) "Centrifugal Pump" Empirical Functional Relationship of $C_p$ to $w_s$
CPB Cycles Per Batch
CPD,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
CVBM Purchased Cost (1993) of Precipitation Drum Vessel
CW Cooling Water cost per year
CWu Unit Cost of Cooling Water ($/Mgal)
D Diameter of Motionless Mixer
DCF After-Tax Discounted Cash Flow
E&HO Engineering and Home Office Expense
Ea Energy Consumed by the Agitator of the Precipitation Drum
ECE Environmental Control Equipment Costs
E_\ell Energy Consumed for Lighting and Heating, Ventilation & Air Conditioning (HVAC) of the BNL plant
Ep1 Energy Consumed by Motor of Pump No.1
Ep2 Energy Consumed by Motor of Pump No.2
Esc Energy Consumed by Motor of Sedimentation Centrifuge
ET 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 ($/yr)
FLBGu Unit Cost of Flexicoker LBG ($/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
FP 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
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPB</td>
<td>Hours Per Batch of Operation of a Motor</td>
</tr>
<tr>
<td>HPB_a</td>
<td>Hours Per Batch of Operation of Agitator of Precipitation Drum</td>
</tr>
<tr>
<td>HPB_p1</td>
<td>Hours Per Batch of Operation of Pump No. 1</td>
</tr>
<tr>
<td>HPB_p2</td>
<td>Hours Per Batch of Operation of Pump No. 2</td>
</tr>
<tr>
<td>HPB_sc</td>
<td>Hours Per Batch of Operation of Sedimentation Centrifuge</td>
</tr>
<tr>
<td>HPY</td>
<td>Hours Per Year of Operation of a Motor</td>
</tr>
<tr>
<td>HPY_a</td>
<td>Hours Per Year of Operation of Agitator of Precipitation Drum</td>
</tr>
<tr>
<td>HPY_p1</td>
<td>Hours Per Year of Operation of Pump No. 1</td>
</tr>
<tr>
<td>HPY_p2</td>
<td>Hours Per Year of Operation of Pump No. 2</td>
</tr>
<tr>
<td>HPY_sc</td>
<td>Hours Per Year of Operation of Sedimentation Centrifuge</td>
</tr>
<tr>
<td>IBP</td>
<td>Initial Boiling Point</td>
</tr>
<tr>
<td>IN</td>
<td>Insurance</td>
</tr>
<tr>
<td>KERNRIV</td>
<td>Kern River (Californian Heavy)</td>
</tr>
<tr>
<td>LB</td>
<td>Annual Labor Cost</td>
</tr>
<tr>
<td>LBG</td>
<td>Low Btu Gas</td>
</tr>
<tr>
<td>LM</td>
<td>Labor Maintenance Costs</td>
</tr>
<tr>
<td>LR</td>
<td>Labor Rate</td>
</tr>
<tr>
<td>lt</td>
<td>Long Ton</td>
</tr>
<tr>
<td>m</td>
<td>Mass Flow Rate Through a vessel</td>
</tr>
<tr>
<td>m_ap</td>
<td>Mass Flow Rate of Bacterial Aqueous Phase exiting the sedimentation centrifuge</td>
</tr>
<tr>
<td>MEXM</td>
<td>Mexican Maya</td>
</tr>
<tr>
<td>MLM(D)</td>
<td>&quot;Motionless Mixer&quot; Empirical Functional Relationship of C_p to diameter D</td>
</tr>
<tr>
<td>MM</td>
<td>Materials Maintenance Costs</td>
</tr>
<tr>
<td>MMT</td>
<td>Motionless Mixer Throughput</td>
</tr>
<tr>
<td>m_o</td>
<td>Mass Flow Rate of Oil Phase exiting the sedimentation centrifuge</td>
</tr>
<tr>
<td>m_p2</td>
<td>Mass Flow Rate Through Pump No. 2</td>
</tr>
<tr>
<td>MFF(F_p x F_m)</td>
<td>&quot;Material and Pressure Factors&quot; Empirical Functional Relationship of Bare Module Factor, F_a_BM, to Material Factor and Pressure Factor for pumps</td>
</tr>
<tr>
<td>m_ps</td>
<td>Mass Flow Rate of Pumped Solution entering the sedimentation centrifuge</td>
</tr>
<tr>
<td>m_sc</td>
<td>Mass Flow Rate Through Sedimentation Centrifuge</td>
</tr>
<tr>
<td>MT</td>
<td>Maintenance</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Fuel Gas</td>
</tr>
<tr>
<td>NR</td>
<td>Net Realization of a Process</td>
</tr>
<tr>
<td>NRB</td>
<td>Net Realization per Barrel of a Process</td>
</tr>
<tr>
<td>O2</td>
<td>Oxygen ($/yr)</td>
</tr>
<tr>
<td>O2a</td>
<td>Unit cost of Oxygen ($/st)</td>
</tr>
<tr>
<td>OC</td>
<td>Annual Operating Costs ($/yr)</td>
</tr>
<tr>
<td>OH</td>
<td>Annual Overhead Costs</td>
</tr>
<tr>
<td>OPC</td>
<td>Oil Product Credits</td>
</tr>
</tbody>
</table>
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 ($/kWh)
q  Volumetric Flow Rate Through a vessel
RG  Refinery Fuel Gas
ROI  Rate Of Return on Total Capital Investment Per Current U.S. Tax
     Structure
RS  Removed Sulfur From Oil Into Bacterial Culture per Batch
S  Amount of Sulfur (wt%) or Simply Sulfur.
SB(P)  "Stuffing Box" Empirical Functional Relationship of Purchased
       Equipment Cost, C_P, to Pressure, P
SC(q)  "Sedimentation Centrifuge" Empirical Functional Relationship of
       Purchased Equipment Cost, C_P, to Volumetric Flow Rate, q
scf  Standard cubic feet, gas measured at 60°F, 1 atm pressure
SCR  Selling Price of By-product Sulfur
SCT  Sedimentation Centrifuge Throughput
SDPY  Stream Days Per Year of Operation of a Motor or Plant
SGAP  Specific Gravity of Aqueous Phase
SGOP  Specific Gravity of Oil Phase
SGPS  Specific Gravity of Pumped Solution Through a Vessel
SO  Shift Overlap
SPR  Sulfur Percent Removed from Heavy Oil by BNL Process
SPROD  Sulfur Weight Content in the Product Oil
SREM   Weight Percent of Product Oil Equal to Amount of Product Sulfur Removed
ST     Steam
st     Short Ton
SUP    Supervision
SWP    Sulfur Weight Percent in Heavy Oil Feed
TCIC   Total Capital Investment Costs
TFC    Total Facilities Costs
ton    Metric Ton
TPPT   Two-Plant Processing Time
UT     Utilities Cost ($/yr)
V      Volume of a Vessel
VB     Venezuelan Bachquero (VB)
VGO    Vacuum Gas Oil
WC     Working Capital
ws     Power of a Motor at the Shaft
ws,a   Power of Agitator of Precipitation Drum at the Shaft
ws,p1  Power of Pump No.1 at the Shaft
ws,p2  Power of Pump No.2 at the Shaft
ws,sc  Power of Sedimentation Centrifuge at the Shaft
WTIM   West Texas Intermediate
ΔP     Differential Pressure Drop Through the Pump
εi     Intrinsic Efficiency of the Pump
η      Efficiency of Motors
ρ      Mass Density of the Fluid Pumped
ρo     Mass Density of Oil Phase
ρw     Mass Density of Water (=1,000 kg/m³)
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 3.39% 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. If 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$/m³ instead of the 10$/m³ 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).
1. Executive Summary

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

<table>
<thead>
<tr>
<th>Processes</th>
<th>Crude Feeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arabian Light</td>
</tr>
<tr>
<td>Delayed Coking</td>
<td>0.05</td>
</tr>
<tr>
<td>Process - 1A</td>
<td></td>
</tr>
<tr>
<td>Process - 2A</td>
<td>0.11</td>
</tr>
<tr>
<td>Process - 2B</td>
<td></td>
</tr>
<tr>
<td>Process - 2C</td>
<td></td>
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<td>Process - 3A</td>
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<td>Process - 3B</td>
<td></td>
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<td>Process - 3C</td>
<td></td>
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<tr>
<td>Process - 4A</td>
<td></td>
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<tr>
<td>Process - 4B</td>
<td></td>
</tr>
<tr>
<td>Process - 4C</td>
<td></td>
</tr>
<tr>
<td>Process - 4D</td>
<td></td>
</tr>
<tr>
<td>Process - 5A</td>
<td></td>
</tr>
<tr>
<td>Process - 5B</td>
<td></td>
</tr>
<tr>
<td>Process - 5C</td>
<td></td>
</tr>
<tr>
<td>Process - 5D</td>
<td></td>
</tr>
<tr>
<td>Process - 6A</td>
<td>0.14</td>
</tr>
<tr>
<td>Process - 7A</td>
<td></td>
</tr>
<tr>
<td>Process - 8A</td>
<td></td>
</tr>
<tr>
<td>Process - 9A</td>
<td></td>
</tr>
<tr>
<td>Process - 9B</td>
<td></td>
</tr>
<tr>
<td>Process - 10A</td>
<td></td>
</tr>
</tbody>
</table>

Note: Values in parenthesis indicate negative quantities.
I. Executive Summary

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

<table>
<thead>
<tr>
<th>Process Parameter #</th>
<th>Process Parameter Name</th>
<th>Process Parameter Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Batch processing time</td>
<td>48 hrs</td>
</tr>
<tr>
<td>2</td>
<td>Temperature</td>
<td>30°C - 40°C</td>
</tr>
<tr>
<td>3</td>
<td>Pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>4</td>
<td>Oil feed/batch</td>
<td>250,000 gal = 946 m³ = 757 ton</td>
</tr>
<tr>
<td>5</td>
<td>Bacterial culture (0.6 of Feed)/batch</td>
<td>150,000 gal = 568 m³ = 568 ton</td>
</tr>
<tr>
<td>6</td>
<td>Bacterial culture cost</td>
<td>$10/m³</td>
</tr>
<tr>
<td>7</td>
<td>Sulfur reduction per batch</td>
<td>33 wt%</td>
</tr>
<tr>
<td>8</td>
<td>Plant operator-year level of labor</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Purchase cost of oil No.6 with 3 wt% sulfur (Process Feed)</td>
<td>$10.775/bbl</td>
</tr>
<tr>
<td>10</td>
<td>Sale price of oil No.6 with 2 wt% sulfur (Product Credit)</td>
<td>$12.70/bbl</td>
</tr>
<tr>
<td>11</td>
<td>Filling factor of bioreactor</td>
<td>80%</td>
</tr>
<tr>
<td>12</td>
<td>Number of recirculations of oil-bacterial solution into the bioreactor per batch</td>
<td>50 cycles</td>
</tr>
<tr>
<td>13</td>
<td>Pump No.1 flow rate</td>
<td>1,030 ton/hr</td>
</tr>
<tr>
<td>14</td>
<td>Pump No.2 Flow Rate</td>
<td>770 ton/hr</td>
</tr>
<tr>
<td>15</td>
<td>Pressure drop across Pump No.1</td>
<td>0.5 atm</td>
</tr>
<tr>
<td>16</td>
<td>Pressure drop across Pump No.2</td>
<td>0.5 atm</td>
</tr>
<tr>
<td>17</td>
<td>Oil-bacterial solution flow rate into sedimentation centrifuge</td>
<td>144 ton/hr</td>
</tr>
<tr>
<td>18</td>
<td>Precipitant flow rate into precipitation drum</td>
<td>1 ton/hr</td>
</tr>
<tr>
<td>19</td>
<td>Volume of precipitation drum</td>
<td>50,000 gal</td>
</tr>
<tr>
<td>20</td>
<td>Filter surface area</td>
<td>10 m²</td>
</tr>
<tr>
<td>21</td>
<td>Diameter of motionless mixer</td>
<td>0.5 m</td>
</tr>
<tr>
<td>22</td>
<td>Efficiency of Pump No.1</td>
<td>0.6</td>
</tr>
<tr>
<td>23</td>
<td>Efficiency of Pump No.2</td>
<td>0.6</td>
</tr>
<tr>
<td>24</td>
<td>Construction material of bioreactor</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>25</td>
<td>Construction material of motionless mixer</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>26</td>
<td>Construction material of Pump No. 1</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>27</td>
<td>Construction material of Pump No. 2</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>28</td>
<td>Construction material of sedimentation centrifuge</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>29</td>
<td>Construction material of precipitation drum vessel</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>30</td>
<td>Construction material of precip. drum agitator</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>31</td>
<td>Type of agitator</td>
<td>Liquid-Liq., Mild, Turbine, Axial</td>
</tr>
<tr>
<td>32</td>
<td>Construction material of filter press</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>33</td>
<td>Type of filter press</td>
<td>Plate and Frame</td>
</tr>
</tbody>
</table>
SFA-Set Parametric Values

34 Plant set-up time  
35 Plant operator-year cost  
36 Stream days per year  
37 Electric power cost  
38 Sale price of elemental sulfur (By-Product Credit)

3 hrs  
$280,670  
330 sd/yr  
$0.05/kWh  
$50/lt

ECI-Set Parametric Values

39 Type of feed  
40 Feed sulfur content  
41 Price of feed  
42 Method of computation of feed price  
43 Slope of feed cost vs sulfur content curve  
44 Intercept of feed cost vs sulfur content curve

High-Sulfur Resid Fuel Oil at NY Harbor  
3 wt% S  
$10.574/bbl  
Least squares fit to prices reported in Platt's Oilgram Price Report, September 14, 1993  
B = -2.024 S/%S  
A = $16.646

Parametric Values Still to be Set by BNL

45 Economic benefits due to wt% reduction of N and O2
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

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

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Base value</th>
<th>New Value</th>
<th>($) New NR/bbl</th>
<th>% Change NR/bbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur in crude</td>
<td>3.00%</td>
<td>3.30%</td>
<td>0.276</td>
<td>+364.7</td>
</tr>
<tr>
<td>Crude cost slope (B)</td>
<td>-2.0240</td>
<td>-2.2264</td>
<td>0.270</td>
<td>+354.2</td>
</tr>
<tr>
<td>Sulfur removed (% of initial)</td>
<td>33.33%</td>
<td>36.67%</td>
<td>0.268</td>
<td>+351.1</td>
</tr>
<tr>
<td>Bacteria cult./oil feed vol. ratio (r)</td>
<td>0.60</td>
<td>0.54</td>
<td>0.156</td>
<td>+162.1</td>
</tr>
<tr>
<td>Price of bacteria ($/m3)</td>
<td>$10.00</td>
<td>$9.00</td>
<td>0.155</td>
<td>+160.5</td>
</tr>
<tr>
<td>Batch Processing Time (hr)</td>
<td>48</td>
<td>43.2</td>
<td>0.153</td>
<td>+157.8</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fixed time)</td>
<td>250,000</td>
<td>275,000</td>
<td>0.142</td>
<td>+138.9</td>
</tr>
<tr>
<td>Number of batch cycles</td>
<td>50</td>
<td>45</td>
<td>0.131</td>
<td>+121.0</td>
</tr>
<tr>
<td>Pump mass flow factor (fixed cycles)</td>
<td>1</td>
<td>1.1</td>
<td>0.121</td>
<td>+103.6</td>
</tr>
<tr>
<td>No. of Employees at a time</td>
<td>2.0</td>
<td>1.8</td>
<td>0.117</td>
<td>+96.2</td>
</tr>
<tr>
<td>Stream days in a year</td>
<td>330</td>
<td>363</td>
<td>0.103</td>
<td>+72.6</td>
</tr>
<tr>
<td>Specific gravity of crude</td>
<td>0.80</td>
<td>0.88</td>
<td>0.071</td>
<td>+19.7</td>
</tr>
<tr>
<td>Solution flow rate into centrifuge</td>
<td>144</td>
<td>158.4</td>
<td>0.070</td>
<td>+17.3</td>
</tr>
<tr>
<td>Sulfur sale value ($/lt)</td>
<td>$50.00</td>
<td>$55.00</td>
<td>0.066</td>
<td>+10.5</td>
</tr>
<tr>
<td>Pump efficiencies</td>
<td>0.6</td>
<td>0.66</td>
<td>0.063</td>
<td>+6.5</td>
</tr>
<tr>
<td>Diameter of motionless mixer</td>
<td>0.5</td>
<td>0.45</td>
<td>0.063</td>
<td>+5.9</td>
</tr>
<tr>
<td>Electric. cost rate ($/kWh)</td>
<td>$0.05</td>
<td>$0.045</td>
<td>0.062</td>
<td>+4.6</td>
</tr>
<tr>
<td>Fraction of tank used</td>
<td>0.8</td>
<td>0.88</td>
<td>0.062</td>
<td>+4.5</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fixed cycles)</td>
<td>250,000</td>
<td>275,000</td>
<td>0.060</td>
<td>+1.0</td>
</tr>
</tbody>
</table>
Figure 1-1 Bar Diagram of the Effect of ± 10% Change in the Input Parameters on the Net Realization Percentage Increase in NR/BBL

- Sulfur in crude
- Crude Cost Slope (B)
- Sulfur removed (% of initial)
- Bacteria cult./oil feed vol. ratio (rv)
- Price of bacteria ($/m3)
- Batch Processing Time (hr)
- Oil to be treated (gal) (fixed time)
- Number of batch cycles
- Pump mass flow factor (fixed cycles)
- No. of Employees at a time
- Stream days in a year
- Specific gravity of crude
- Solution flow rate into centrifuge
- Sulfur sale value ($/ft)
- Pump efficiencies
- Diameter of Motionless mixer
- Electric cost rate ($/kWh)
- Fraction of tank used
- Oil to be treated (gal) (fixed cycles)
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)
2. Computation Basis

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

\[ \text{TCIC} = \text{TFC} + \text{E\&HO} + \text{PSU} + \text{PR} + \text{WC} \] (2-1)

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)

\[ \text{TFC} = \text{BLE} + \text{UT} + \text{GF} \] (2-2)

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

\[ \text{BLE} = 1.1 \times \{\text{Production Equip.} + \text{Environm. Controls Equip.}\} \] (2-3)

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
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)

\[
GF = 0.35 \times BLE
\]  \hspace{1cm} (2-4)

\[
E&HO = 0.10 \times TFC
\]  \hspace{1cm} (2-5)

\[
PSU = 0.05 \times TFC
\]  \hspace{1cm} (2-6)

\[
PR = 0.02 \times TFC
\]  \hspace{1cm} (2-7)

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)

\[
WC = 0.01 \times TFC + 20 \times FEEDD
\]  \hspace{1cm} (2-8)

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)

\[
OC = FEEDA + FG + UT + CAT + LB + MT + [OH + PT + IN] + CC
\]  \hspace{1cm} (2-9)
2. Computation Basis

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)

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

2.1.11 Refinery Fuel Gas (RG)

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

2.1.12 Low Btu Gas (LBG)

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

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

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

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 (O₂)
- Boiler feed water cost per year (BFW)
- Cooling water cost per year (CW)

\[ \text{UT} = \text{PW} + \text{ST} + \text{O₂} + \text{BFW} + \text{CW} \] (2-25)

The unit cost of each form of energy above are:
PW_u = 0.05 $/kWh \quad (2-26)

ST_u = 5.00 $/Mlb \quad (2-27)

O_{2u} = 35 $/st \quad (2-28)

BFW_u = 1.00 $/Mgal \quad (2-30)

CW_u = 0.10 $/Mgal \quad (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)

\[ 1 \text{ st} = \text{short ton} = 2000 \text{ lb} = 907 \text{ kg} \quad (2-29) \]

\[ 1 \text{ Mgal} = 3785.4 \text{ Ml} \]

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 \quad (2-32)

CHM = 0.06 $/Mscf \quad (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)

\[ LR = 18.00 \text{ $/hr} \quad (2-34) \]

\[ SUP = 0.20 \times LR \quad (2-35) \]

\[ PB = 0.35 \times \{LR+SUP\} = 0.42 \times LR \quad (2-36) \]

\[ SO = 0.10 \times \{LR+SUP+PB\} = 0.16 \times LR \quad (2-37) \]
2. Computation Basis

\[ \text{LB} = \text{LR} + \text{SUP} + \text{PB} + \text{SO} = 1.78 \times \text{LR} \quad \text{(2-38)} \]
\[ \text{LR Hours/Plant Operator-Year} = 8,760 \text{ hrs} \quad \text{(2-39)} \]
\[ \text{LB/Plant Operator-Year} = 1.78 \times 8,760 \times 18 = 280,670 \quad \text{(2-40)} \]

2.1.16 Maintenance (MT)
Maintenance costs include the following items:
- Labor Maintenance costs (LM)
- Materials Maintenance costs (MM)

\[ \text{MT} = \text{LM} + \text{MM} \quad \text{(2-41)} \]
\[ \text{MT} = 0.02 \times \text{TCIC} \quad \text{(2-42)} \]

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

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

2.1.18 Capital Charges (CC)

\[ \text{CC} = 0.20 \times \text{TCIC} \quad \text{(2-44)} \]
\[ \text{CC} = \text{FYPBBT} \quad \text{(2-45)} \]

where FYPBBT = 5-Year Payback Before Taxes

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

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 (\(\text{SCR}\))
- 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:

\[
S_u = 50 \$/lt
\]  \hspace{1cm} (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

\[
1 \text{ lt} = \text{long ton} = 2,240 \text{ lbs} = 1,016 \text{ kg}
\]  \hspace{1cm} (2-48)

Similarly,

\[
FLBG_u = 10 \$/FOE bbl \hspace{1cm} (2-49)
\]

\[
PC_u = 5.00 \$/st \hspace{1cm} (2-50)
\]

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

\[
PLS_u = 10 \$/bbl \hspace{1cm} (2-51)
\]

When the sulfur content is lower than 2 wt%

\[
PHS_u = 5 \$/bbl \hspace{1cm} (2-52)
\]

\[
ASPH_u = 20 \$/st = 4.60 \$/bbl \hspace{1cm} (2-53)
\]

2.1.20 Conversion Unit Product Prices

The following are the prices for the virgin IBP/650°F (342°F) and for the upgraded C5/VGO products, so that the net realization of the delayed coking of Arabian Light crude is approximately zero:

\[
\text{IBP}/650^\circ F \text{ at } 20 \text{ °API liquid gravity} = 20 \$/bbl \hspace{1cm} (2-54)
\]
\[
\text{IBP}/650^\circ F \text{ at } 30 \text{ °API liquid gravity} = 21 \$/bbl \hspace{1cm} (2-55)
\]
\[
\text{IBP}/650^\circ F \text{ at } 40 \text{ °API liquid gravity} = 21.8 \$/bbl \hspace{1cm} (2-56)
\]
\[
\text{IBP}/650^\circ F \text{ at } 50 \text{ °API liquid gravity} = 22.5 \$/bbl \hspace{1cm} (2-57)
\]

where \( \text{IBP}/650^\circ F = \text{Virgin cut at initial boiling point of } 650^\circ F \text{ (342°F)} \)

\[
\text{C}_5/\text{VGO} \text{ at } 20 \text{ °API liquid gravity} = 21 \$/bbl \hspace{1cm} (2-58)
\]
\[
\text{C}_5/\text{VGO} \text{ at } 30 \text{ °API liquid gravity} = 22.8 \$/bbl \hspace{1cm} (2-59)
\]
2. Computation Basis

C₅/VGO at 40 °API liquid gravity = 24.5 $/bbl
(2-60)

where C₅/VGO = C₅ 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)

\[
CR = OPC + BPC
\]
(2-61)

2.1.22 Net Realization (NR)

\[
NR = CR - OC
\]
(2-62)

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:

\[
BF = HO + BC
\]
(2-63)

where:
- BF = Bioreactor Fluids/batch
- HO = Heavy Oil/batch
- BC = Bacterial Culture/batch
In the Base Case (Table 1-2, Figure 2-1):

\[ BF = 757 + 568 = 1325 \text{ ton/batch} \]  
\[ (2-64) \]

### 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:

\[ \text{BPT} = \left( \frac{\text{BF}}{\text{MMT}} \right) \times \text{CPB} \]  
\[ (2-65) \]

where:

- \( \text{BPT} = \) Bioreactor Processing Time
- \( \text{MMT} = \) Motionless Mixer Throughput
- \( \text{CPB} = \) Cycles Per Batch

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

\[ \text{BPT} = \left( \frac{1325 \text{ ton/batch}}{1800 \text{ ton/hr}} \right) \times 50 = \]  
\[ = [0.736 \text{ hr/batch}] \times 50 = 36.8 \text{ hrs/batch} \]  
\[ (2-66) \]

### 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:

\[ \text{PRT} = \frac{BF}{SCT} \]  
\[ (2-67) \]

where:

- \( \text{PRT} = \) Product Recovery Time
- \( \text{SCT} = \) Sedimentation Centrifuge Throughput

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

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

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:

\[ \text{AP} = \text{BC} + \text{RS} \quad (2-69) \]

where:

- \( \text{AP} \) = Aqueous Phase Processed Through the Precipitation Drum/Batch
- \( \text{BC} \) = Bacterial Culture/Batch
- \( \text{RS} \) = Removed Sulfur From Oil Into Bacterial Culture/Batch

\[ \text{RS} = \text{HO} \times \text{SWP} \times \text{SPR} \quad (2-70) \]

where:

- \( \text{SWP} \) = Sulfur Weight Percent in Heavy Oil Feed
- \( \text{SPR} \) = Sulfur Percent Removed from Heavy Oil by BNL process

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

\[ \text{AP} = 568 \text{ ton/batch} + 757 \text{ ton/batch} \times 0.03 \times 0.33 \]
\[ = 575.49 \text{ ton/batch} \quad (2-71) \]

2.2.5 Processing Time of Aqueous Phase in Precipitation Drum

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

\[ \text{PDPT} = \frac{\text{AP} + \text{PRE}}{\text{PDT}} \quad (2-72) \]

where:

- \( \text{PDPT} \) = Precipitation Drum Processing Time
PRE  = Amount of Precipitant/Batch
PDT  = Precipitation Drum Throughput

\[ PRE = AP \times [PRFR/APFR] \]  

(2-73)

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:

\[ PDPT = AP \times \left[1 + \frac{PRFR}{APFR}\right] / PDT \]  

(2-74)

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

\[ PDPT = 575.49 \text{ ton/batch} \times \left[1 + \frac{1\text{ton/hr}}{62.5\text{ton/hr}}\right] / 63.5 \text{ ton/hr} \]
\[ = 9.21 \text{ hr/batch} \]  

(2-75)

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. :

\[ \text{PRT} = \text{PDPT} \]  

(2-76)

2.2.6 Two-Plant Processing Time Per Batch
The sum of the processing time of the two plants is:

\[ \text{TPPT} = \text{BPT} + \text{PRT} = \text{BPT} + \text{PDPT} \]  

(2-77)

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):

\[ \text{TPPT} = 36.8 + 9.2 = 46 \text{ hrs} \]  

(2-78)

2.2.7 Batch Total Processing Time
2. Computation Basis

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:

\[ BTPT = TPPT + PSUT \]  

(2-79)

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

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

\[ BTPT = 46 \text{ hrs} + 2 \text{ hrs} = 48 \text{ hrs} \]  

(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.:
\[ V = \text{BF} / \text{FF} \]  \hfill (2-81)

where:
- \( V \) = Tank's volume
- \( \text{BF} \) = Bioreactor Fluids/batch
- \( \text{FF} \) = Filling Factor (or percentage of total volume filled)

Inserting \( \text{BF} \) from eqn. 2-63 into eqn. 2-81 yields:

\[ V = \left[ \text{HO} + \text{BC} \right] / \text{FF} \]  \hfill (2-82)

where:
- \( \text{HO} \) = Heavy Oil/batch
- \( \text{BC} \) = Bacterial Culture/batch

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

\[ V = \left[ 250,000 + 150,000 \right] \text{gal} / 0.8 = 500,000 \text{gal} \]  \hfill (2-83)

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

\[ 1 \text{ gal} = 3.785411 \times 10^{-3} \text{ m}^3 \]  \hfill (2-84)

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

\[ V = 1,892.71 \text{ m}^3 \]  \hfill (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:

\[ C_p = \text{CR}(V) \]  \hfill (2-86)

where:
- \( C_p \) = Purchased equipment cost
- \( \text{CR}(V) \) = "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:
2. Computation Basis

\[ C_P = 43,090 \]  \hspace{2cm} (2-87)

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:

\[ F_{BM} = 1.9 \]  \hspace{2cm} (2-88)

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

\[ C_{BM} = C_P \times F_{BM} \]  \hspace{2cm} (2-89)

Inserting \( C_P \) from eqn. 2-87 and \( F_{BM} \) from eqn. 2-88 into eqn. 2-89 yields:

\[ C_{BM,1982} = 43,090 \times 1.9 = 81,871 \]  \hspace{2cm} (2-90)

The Bare Module Cost for 1993 is:

\[ C_{BM,1993} = C_{BM,1982} \times \frac{[CEAI_{1993}]}{CEAI_{1982}} \]  \hspace{2cm} (2-91)

where:

\[ CEAI = \text{Chemical Engineering Plant Cost Annual Index} \]

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

\[ CEAI_{1993} = 359.2 \]  \hspace{2cm} (2-92)

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

\[ CEAI_{1982} = 315 \]  \hspace{2cm} (2-93)

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

\[ \frac{CEAI_{1993}}{CEAI_{1982}} = \frac{359.2}{315} = 1.1403 \]  \hspace{2cm} (2-94)
Eqn. 2-91 and eqn. 2-94 give:

\[ C_{BM,1993} = C_{BM,1982} \times 1.1403 \]  \hspace{1cm} (2-95)

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

\[ C_{BM,1993} = 81,871 \times 1.1403 = 93,359 \]  \hspace{1cm} (2-96)

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:

\[ C_p = MLM(D) \]  \hspace{1cm} (2-97)

where:

\( C_p \) = MLM = "Motionless Mixer" Empirical Functional Relationship of \( C_p \)
\( D \) = Diameter of Motionless Mixer

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

\[ C_p = 13,264 \]  \hspace{1cm} (2-98)

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

\[ F_{BM} = 2.9 \]  \hspace{1cm} (2-99)

where:

\( F_{BM} \) = Bare Module Factor

The insert equation of Fig. 5-41 gives:

\[ C_{BM} = C_p \times F_{BM} \]  \hspace{1cm} (2-100)

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:
2. Computation Basis

\[ C_{BM} = 13,264 \times 2.9 = 38,465 \]  \hspace{1cm} (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:

\[ C_{BM,1993} = 38,465 \times 1.1403 = 43,862 \]  \hspace{1cm} (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:

\[ w_s = \frac{q\Delta P}{\varepsilon_i} \]  \hspace{1cm} (2-103)

where:

- \( w_s \) = Power at the pump shaft
- \( q \) = Volumetric flow rate through the pump
- \( \Delta P \) = Differential pressure drop through the pump
- \( \varepsilon_i \) = Intrinsic efficiency of the pump

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

\[ q = \frac{m}{\rho} \]  \hspace{1cm} (2-104)

where:

- \( m \) = Mass flow rate through the pump
- \( \rho \) = Mass density of the fluid pumped

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

\[ w_s = \frac{m\Delta P}{\rho\varepsilon_i} \]  \hspace{1cm} (2-105)
The mass density of the fluid pumped, \( \rho \), is expressed in terms of specific gravity by:

\[
\rho = \text{SGPS} \ \rho_w
\]  

(2-106)

where:

\( \text{SGPS} \) = Specific gravity of pumped solution  
\( \rho_w \) = Mass density of water

Substituting the mass density of the fluid pumped, \( \rho \), from eqn. 2-106 into eqn. 2-105 yields:

\[
\dot{w}_S = \frac{m \Delta P}{\text{SGPS} \ \rho_w \ \epsilon_i} 
\]  

(2-107)

The mass density of water, \( \rho_w \), is:

\( \rho_w = 1,000 \ \text{kg/m}^3 \)  

(2-108)

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

\[
m = \frac{1030 \text{ton} \times 1000 \text{kg/ton}}{3600 \text{sec}} = 286 \ \text{kg/sec} 
\]  

(2-109)

Experimental tests showed that the specific gravity of the pumped solution, \( \text{SGPS} \), for the Base Case was:

\( \text{SGPS} = 0.8 \)  

(2-110)

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

\( \Delta P = 0.5 \ \text{atm} \)  

(2-111)

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

\[
1 \ \text{atm} = 1.01325 \times 10^5 \ \text{N/m}^2 
\]  

(2-112)

The intrinsic efficiency of the pump was selected for the Base Case to be (Ulrich p.205, Table 4-20):
Inserting \( m \) from eqn. 2-109, \( \Delta P \) from eqn. 2-111, SGPS from eqn. 2-110, \( \rho_w \) from eqn. 2-108, atm from eqn. 2-112, and \( \varepsilon_i \) from eqn. 2-113 into eqn. 2-107 yields:

\[
W_s = \frac{286 \text{kg/sec} \times 0.5 \times 1.01325 \times 10^5 \text{N/m}^2}{0.8 \times 1000 \text{kg/m}^3 \times 0.6} = \\
= 30,186.4 \text{ (Nm/sec)} = 30.2 \text{ kW} \tag{2-114}
\]

Ulrich's Fig. 5-49 (p. 310), or Fig. 2-6 in the present report, gives \( C_P \) as an empirical functional relationship to \( W_s \), i.e.:

\[
C_P = C_P(W_s) \tag{2-105}
\]

where:

\( C_P(W_s) = \) Centrifugal Pump functional relationship of \( C_P \) to \( W_s \)

Figure 2-6, for centrifugal pump, and for \( W_s \) equal to 30 kW, produces:

\[
C_P = $10,617 \tag{2-116}
\]

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

\[
C_{BM} = C_P \times F_{BM} \tag{2-117}
\]

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:

\[
F_M = 1.4 \tag{2-118}
\]

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, $p_1$, for three different types of pumps: centrifugal, rotary with positive displacement, and reciprocating. For centrifugal pumps:

$$F_p = C_p(p_1)$$  \hspace{1cm} (2-119)

where:

$C_p(p_1) =$ Centrifugal Pump Functional Relationship of $F_p$ on $p_1$

The Base Case assumes a barometric pressure inside the bioreactor equal to 1 atm. Fig. 5-50 gives $p_1$ 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 $p_1$ values less than 10, no pressure correction is needed, and:

$$F_p = 1.0$$  \hspace{1cm} (2-120)

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:

$$F_{BM} = MPF(F_p \times F_M)$$  \hspace{1cm} (2-121)

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:

$$[F_p \times F_M] = 1.0 \times 1.4 = 1.4$$  \hspace{1cm} (2-122)

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

$$F_{BM} = 4.05$$  \hspace{1cm} (2-123)

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

\[ C_{BM} = 10,617 \times 4.05 = 42,999 \]  

(2-124)

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

\[ C_{BM, 1993} = 42,999 \times 1.1403 = 49,031 \]  

(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:

\[ m = 770 \text{ ton/hr} = 770,000 \text{ kg/3600 sec} = 213.89 \text{ kg/sec} \]  

(2-126)

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

\[ S_{Gw} = 1.0 \]  

(2-127)

where:

\[ S_{Gw} = \text{Specific Gravity of Water} \]

Therefore:

\[ S_{GPS} = 1.0 \]  

(2-128)

where:

\[ S_{GPS} = \text{Specific gravity of pumped solution} \]

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:

\[ \Delta P = 0.5 \text{ atm} \]  

(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:

\[ \varepsilon_i = 0.6 \]  

(2-130)

Inserting \( m \) from eqn. 2-126, \( \Delta P \) from eqn. 2-129, \( \varepsilon_i \) from eqn. 2-130, \( S_{GPS} \) from eqn. 2-128, \( \rho_w \) from eqn. 2-108, and atm from eqn. 2-112 into eqn. 2-107, yields:
2. Computational Basis

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

\[ = 18,060.33 \text{ W} = 18.1 \text{ kW} \quad (2-131) \]

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:

\[ C_p = 8,649 \quad (2-132) \]

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

\[ F_M = 1.4 \quad (2-133) \]

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:

\[ F_p = 1.0 \quad (2-134) \]

Therefore:

\[ [F_p \times F_M] = 1.0 \times 1.4 = 1.4 \quad (2-135) \]

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:

\[ F_{BM} = 4.05 \quad (2-136) \]

Inserting \(C_p\) from eqn. 2-132 and \(F_{BM}\) from eqn. 2-136 into eqn. 2-117 yields:

\[ C_{BM,1982} = 8,649 \times 4.05 = 35,028 \quad (2-137) \]

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

\[ C_{BM,1993} = 35,028 \times 1.1403 = 39,943 \quad (2-138) \]

2.3.5 Sedimentation Centrifuge Separator

Inserting the mass density of the pumped solution, \(\rho\), from eqn. 2-106 into eqn. 2-104 yields:
2. Computation Basis

\[ q = \frac{m}{SGPS \rho_w} \]  

(2-139)

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

\[ m = 144 \text{ ton/hr} = 144,000 \text{ kg/3,600 sec} = 40 \text{ kg/sec} \]  

(2-140)

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

\[ SGPS = \frac{m_o}{m_{ps}} SGOP + \frac{m_{ap}}{m_{ps}} SGAP \]  

(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 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:

\[ m_o = 83 \text{ ton/hr} \]  

(2-142)

\[ m_{ps} = 144 \text{ ton/hr} \]  

(2-143)

\[ m_{ap} = 61 \text{ ton/hr} \]  

(2-144)

Figure 2-1 gives for the feed oil the following oil-phase amounts per batch:
Oil Phase/batch = 250,000 gal/batch = 757 ton/batch \hspace{1cm} (2-145)

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

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

where:

$\text{ton} = \text{metric ton}$

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

\[250,000 \text{ gal} \times 3.78541 \times 10^{-3} \text{ m}^3/\text{gal of oil phase} = \]
\[= 757 \text{ ton} \times 1,000 \text{ kg/ton of oil phase} \]

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:

$\rho_o = 800 \text{ kg/m}^3 \hspace{1cm} (2-147)$

where:

$\rho_o = \text{Mass Density of Oil Phase}$

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:

$\boxed{\text{SGOP} = \frac{\rho_o}{\rho_w}} \hspace{1cm} (2-148)$

where:

$\text{SGOP} = \text{Specific Gravity of Oil Phase}$

Inserting $\rho_w$ from eqn. 2-108 and $\rho_o$ from eqn. 2-147 into eqn. 2-148 yields:

$\text{SGOP} = \frac{[800 \text{ kg/m}^3]}{[1000 \text{ kg/m}^3]} = 0.8 \hspace{1cm} (2-149)$

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

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:

\[
\text{SGAP} = 1 \tag{2-150}
\]

Inserting \( m_0 \) from eqn. 2-142, \( m_{PS} \) from eqn. 2-143, \( m_{AP} \) from eqn. 2-144, \( \text{SGOP} \) from eqn. 2-149 and \( \text{SGAP} \) from eqn. 2-150 into eqn. 2-140 yields:

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

Inserting \( m \) from eqn. 2-140, \( \text{SGPS} \) from eqn. 2-151, and \( \rho_w \) 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:

\[
C_P = SC(q) \tag{2-153}
\]

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:

\[ V = 50,000 \text{ gal} \]  \hspace{1cm} (2-158)

where:
\( V \) = Volume of precipitation drum

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

\[ V = 50,000 \text{ gal} \times 3.785411 \times 10^{-3} \text{ m}^3/\text{gal} = 189.27 \text{ m}^3 \]  \hspace{1cm} (2-159)

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:

\[
C_p = B_{0.10}(V)
\]  \hspace{1cm} (2-160)

where:
\( C_p \) = Purchased equipment cost
\( B_{0.10}(V) \) = Bullet 0-10 barg functional relationship of \( C_p \) to \( V \).

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

\[ C_p = $45,068 \]  \hspace{1cm} (2-161)

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

\[ FBM = 1.9 \]  \hspace{1cm} (2-162)

Inserting \( C_p \) from eqn. 2-161 and \( FBM \) from eqn. 2-150 into eqn. 2-89 yields:

\[ C_{BM} = $45,068 \times 1.9 = $85,629 \]  \hspace{1cm} (2-163)

This is a 1982 cost. Inserting \( C_{BM,1982} \) from eqn. 2-163 into eqn. 2-96 yields:
2. Computation Basis

\[ C_{BM,1993} = 85,629 \times 1.1403 = 97,643 \]  \hspace{1cm} (2-164)

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:

\[ \text{Power (P) Range} = 0.1 \times V^{0.8} - 0.2 \times V^{0.8} \]  \hspace{1cm} (2-165)

By selecting the upper limit of power:

\[ P = 0.2 \times V^{0.8} \]  \hspace{1cm} (2-166)

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

\[ P = 0.2 \times [189.27 \text{ m}^3]^{0.8} = 13.26 \text{ kW} \]  \hspace{1cm} (2-167)

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

\[ C_p = \text{SB}(P) \]  \hspace{1cm} (2-168)

where:

\[ C_p = \text{Purchased Equipment Cost} \]
\[ \text{SB}(P) = \text{"Stuffing Box" Empirical Functional Relationship of } C_p \text{ to } P \]

Ulrich's Fig.5-42 at \( P = 13.26 \text{ kW} \) gives:

\[ C_p = $13,994 \]  \hspace{1cm} (2-169)

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

\[ F_{BM} = 2.5 \]  \hspace{1cm} (2-170)

Inserting \( C_p \) from eqn. 2-169 and \( F_{BM} \) from eqn. 2-170 into eqn. 2-89 yields:

\[ C_{BM} = $13,994 \times 2.5 = $34,985 \]  \hspace{1cm} (2-171)
This is a 1982 cost. Putting $C_{BM,1982}$ from eqn. 2-171 into eqn. 2-95 yields:

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

The overall cost of the precipitation drum is:

$$C_{PD_{BM}} = C_{V_{BM}} + C_{A_{BM}} \quad (2-173)$$

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:

$$C_{PD_{BM}} = \$97,643 + \$39,893 = \$137,536 \quad (2-174)$$

### 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:

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

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:

$$C_p = PF(A) \quad (2-176)$$

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 $A = 10 \text{ m}^2$ gives:

$$C_p = \$7,325 \quad (2-177)$$
2. Computation Basis

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

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bioreactor (Section 2.3.1)</td>
<td>93,359</td>
</tr>
<tr>
<td>2. Motionless Mixer (Section 2.3.2)</td>
<td>43,862</td>
</tr>
<tr>
<td>3. Pump No.1 (Section 2.3.3)</td>
<td>49,031</td>
</tr>
<tr>
<td>4. Pump No.2 (Section 2.3.4)</td>
<td>39,943</td>
</tr>
<tr>
<td>5. Sedimentation Centrifuge Separator (Section 2.3.5)</td>
<td>328,653</td>
</tr>
<tr>
<td>6. Precipitation Drum (Section 2.3.6)</td>
<td>137,536</td>
</tr>
<tr>
<td>7. Filter Press (Section 2.3.7)</td>
<td>29,234</td>
</tr>
<tr>
<td>8. Single Phase Holding Tank (Section 2.3.8)</td>
<td>--</td>
</tr>
</tbody>
</table>

Total Product. + Environ. Controls Equip. Cost = $721,618

Thus:

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

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

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

\[ ST = 0 \]  \hspace{1cm} (2-183)

where:

\[ ST = \text{Cost of steam} \]

\[ O_2 = 0 \]  \hspace{1cm} (2-184)

where:

\[ O_2 = \text{Cost of oxygen} \]

\[ BFW = 0 \]  \hspace{1cm} (2-185)

where:

\[ BFW = \text{Cost of boiler feed water} \]

\[ CW = 0 \]  \hspace{1cm} (2-186)

where:

\[ CW = \text{Cost of cooling water} \]

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:

\[ E_T = E_{p1} + E_{p2} + E_{sc} + E_a + E_{\ell} \]  \hspace{1cm} (2-187)

where:

\[ E_T = \text{Total energy consumed by the motors and the lighting and HVAC systems of the upgrading plant} \]

\[ E_{p1} = \text{Energy consumed by motor of pump No.1} \]

\[ E_{p2} = \text{Energy consumed by motor of pump No.2} \]
2. Computation Basis

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

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

\[
E_t = PC_{pm} \times [E_{p1} + E_{p2} + E_{sc} + E_a]
\]  
(2-188)

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

Inserting \( E_t \) from eqn. 2-188 into eqn. 2-187 yields:

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

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:

\[
w_{s,sc} = w_{s,p2} \frac{m_{sc}}{m_{p2}}
\]  
(2-190)

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

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:

\[
E = \frac{w_s}{\eta} \text{HPY}
\]  

(2-191)

\( w_s \) = Shaft power of motor
\( \text{HPY} \) = Hours per year of motor operation
\( \eta \) = 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:

\[
\text{HPY} = \text{BPY} \times \text{HPB}
\]  

(2-192)

where:

\( \text{BPY} \) = Number of process batches per year
\( \text{HPB} \) = Hours per batch of motor operation

The annual batches of process operation are given by:

\[
\text{BPY} = \frac{\text{SDPY} \times 24 \text{ hr/sd}}{\text{BTPT}}
\]  

(2-193)

where:

\( \text{SDPY} \) = Stream days per year
\( \text{BTPT} \) = Batch Total Processing Time

Table 2-1 indicates that for the Base Case:

\[
\text{SDPY} = 330 \text{ sd/yr}
\]  

(2-194)

\[
\text{BTPT} = 48 \text{ hrs/batch}
\]  

(2-195)

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

\[
\text{BPY} = \frac{330 \text{ sd/yr} \times 24 \text{ hr/sd}}{48 \text{ hr/batch}} = 165 \text{ batch/yr}
\]  

(2-196)
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:

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

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:

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

Inserting $\text{BPY}$ from eqn. 2-196 and $\text{HPB}_{p1}$ from eqn. 2-198 into eqn. 2-192 yields:

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

Similarly inserting $\text{BPY}$ from eqn. 2-196 and $\text{HPB}_{p2}$ from eqn. 2-197 into eqn. 2-192 yields:

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

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

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

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

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

Figure 2-1 indicates that:

$$\text{msc} = 144 \text{ ton/hr}$$ (2-203)

$$\text{mp}_2 = 770 \text{ ton/hr}$$ (2-204)

2-32
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:

$$w_{s,sc} = 18.1 \text{ kW} \times \frac{144}{770} = 3.38 \text{ kW} \quad (2-205)$$

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 144 ton/hr. Therefore, the time per batch that the sedimentation centrifuge motor must be in operation is:

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

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

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

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

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

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:

$$HPB_{a} = \frac{568 \text{ ton}}{62.5 \text{ ton/hr}} = 9.1 \text{ hrs} \quad (2-209)$$

Inserting $BPY$ from eqn. 2-196 and $HPB_{a}$ from eqn. 2-209 into eqn. 2-192 yields:

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

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

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

\[ PC_{pm} = 0.03 \]  
\[ (2-212) \]

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:

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

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.

\[ PW = E_T \times PW_u \]  
\[ (2-214) \]

Therefore:

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

### 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:

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

### 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:

\[ GF = 0.35 \times 793,780 = 277,823 \]  
\[ (2-217) \]

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

\[ TFC = 793,780 + 20,492 + 277,823 = 1,092,095 \]  
\[ (2-218) \]

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

\[ E&HO = 0.10 \times 1,092,095 = 109,210 \]  
\[ (2-219) \]
Inserting TFC from eqn. 2-218 into eqn. 2-6 yields:

\[
\text{PSU} = 0.05 \times 1,092,095 = 54,605
\]  

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

\[
\text{PR} = 0.02 \times 1,092,095 = 21,842
\]

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:

\[ C = A + B \times S \]  

where:

\[ C = \text{Cost of NY cargo resid fuel oil per barrel} \]

\[ A = 16.646 \]  

\[ B = -2.024 \]

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

\[ C = 16.646 - 2.024 \times 3 = 10.574 \text{ \$ / bbl} \]

Thus, the cost of daily feed is:

\[
\text{FEEDA} = \left[ \frac{250,000 \text{ gal}}{(2 \text{ days} \times 42 \text{ gal/bbl})} \right] \times 10.574 \text{ \$/bbl} = 31,470 \text{ \$/day}
\]
Inserting TFC from eqn. 2-218, and FEEDD from eqn. 2-226 into eqn. 2-8 yields:

\[ WC = 0.01 \times 1,092,095 + 20 \times 31,470 = $640,321 \]  \hspace{1cm} (2-227)

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:

\[ TCIC = 1,092,095 + 109,210 + 54,605 + 21,842 + 640,321 = $1,918,073 \]  \hspace{1cm} (2-228)

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

\[ FEEDA = SDPY \times FEEDD \]  \hspace{1cm} (2-229)

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:

\[ FEEDA = 330 \times 31,470 = 10,385,100 \text{ $/yr} \]  \hspace{1cm} (2-230)

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

\[ FG = 0 \]  \hspace{1cm} (2-231)

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\$/m³. Therefore, the cost of bacterial culture (or Catalyst) per year is:

\[ CAT = 10 \text{ $/m}^3 \times [150,000 \text{ gal/2 sd}] \times 330 \text{ sd/yr} \times 3.785411 \times 10^{-3} \text{ m}^3/\text{gal} = 936,890 \text{ $/yr} \]  \hspace{1cm} (2-232)
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:

\[ LB = \frac{280,670 \$/\text{Plant Operator-Year}}{\text{Plant Operator-Year}} \times 2 \{\text{Plant Operator-Year}\} = \frac{561,340 \$/\text{yr}}{} \]  
(2-233)

where:
LB = Annual Labor Cost

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

\[ MT = 0.02 \times 1,918,073 = 38,361 \$/\text{yr} \]  
(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:

\[ \{\text{OH} + \text{PT} + \text{IN}\} = 0.04 \times \{1,918,073 - 640,321 - 21,842\} = \frac{50,236 \$/\text{yr}}{} \]  
(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:

\[ CC = 0.2 \times 1,918,073 = \$383,615 \]  
(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:
2. Computation Basis

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

where:
\[ OC = \text{Annual Operating Cost} \]

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

\[ \text{PROD}_0 = \left( \frac{250,000 \text{ gal}/2\text{sd}}{42 \text{ gal/bbl}} \right) \times 330 \text{ sd/yr} = 982,143 \text{ bbl/yr} \]  (2-238)

where:
\[ \text{PROD}_0 = \text{Annual Amount of Product Oil} \]

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:

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

where:
\[ \text{SPROD} = \text{Sulfur Weight Content in the Product Oil} \]

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

\[ C = 16.646 - 2.024 \times 2.00 = 12.598 \text{$/bbI} \]  (2-240)

where:
\[ C = \text{Cost of Resid Fuel Oil} \]

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

\[ \text{OPC} = C \times \text{PROD}_0 \]  (2-241)

where:
OPC = Oil Product Credit

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

\[ \text{OPC} = 12.598 \$/bbl \times 982,143 \text{ bbl/yr} = 12,373,038 \$/\text{yr} \quad (2-242) \]

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:

\[ \text{PRODS} = SREM \times \text{PRODOT} \quad (2-243) \]

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:

\[ SREM = 0.33 \times 3 = 1 \text{ wt\% S} \quad (2-244) \]

and

\[ \text{PRODOT} = (757 \text{ ton} / 2\text{sd}) \times 330 \text{ sd/yr} = 124,905 \text{ ton/yr} \quad (2-245) \]

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

\[ \text{PRODS} = 0.01 \times 124,905 \text{ ton/yr} = 1,249 \text{ ton/yr} \quad (2-246) \]

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

\[ 1 \text{ lt} = 1.016 \text{ ton} \quad (2-247) \]

where lt represents a long ton.

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

\[ \text{PRODS} = 1,249 / 1.016 = 1,229 \text{ lt/yr} \quad (2-248) \]
2. Computation Basis

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

\[
BPC = S_u \times PRODS
\]  
(2-249)

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:

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

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

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

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:

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

where:
- \(NR\) = Annual Net Realization of BNL process.

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

\[
NRB = \frac{NR}{PRODO}
\]  
(2-253)

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:

\[
NRB = \frac{58,454 \$/\text{yr}}{982,143 \text{ bbl/yr}} = 0.0595 - 0.06 \$/\text{bbl}
\]  
(2-254)
Table 2-1  Ulrich's Table 4-16: Criteria and Data for the Preliminary Design of Agitators and Mixers.

<table>
<thead>
<tr>
<th>Type of Mixer</th>
<th>Fluid Agitated</th>
<th>Type of Mixer</th>
<th>Mechanically Agitated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fluid Agitated</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outlet valve (gpm)</td>
<td>Mechanical speed</td>
<td>Gas pressure</td>
</tr>
<tr>
<td>Fluid Agitated</td>
<td>0.005-0.5</td>
<td>0.06-1.0</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Agitator diameter, D (m)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Vessel diameter, D (m)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Vessel volume, V (m³)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Mixed fluid flow rate, m (gph)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Liquid</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Gas</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Typical residence time, t (s)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Mixing</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Solid-liquid extraction</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Chemical reaction</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Viscosity range (m Pa s)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Volume fraction of dispersed phase, φ</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Turbulent</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Gas-liquid mixing</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Liquid-liquid mixing (miscible)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Liquid-liquid dispersion (nonmiscible)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Paper pulp mixing</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Non-Newtonian fluids</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Chemical reaction</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Mixing of sticky materials</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Pressure Differential, p (psig)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Power consumption, P (hp)</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
<td>0.01-0.5</td>
</tr>
<tr>
<td>Gas</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>Liquid</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>Viscous</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>Non-Newtonian</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>Solid-Solid</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>Mixing of sticky materials</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
<tr>
<td>See Figure 3-17</td>
<td>1.0-1.5</td>
<td>0.005-0.01</td>
<td>0.25-0.6</td>
</tr>
</tbody>
</table>

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.

*aGas fluxes typically range from 0.004 to 0.05 m³/s per square meter of vessel cross section. Bubble rise velocities normally fall between 0.10 and 0.30 m/s. For detailed design procedures, see J. N. Tilton and W. F. Tutton, "Designing Gas-Sparged Vessels for Mass Transfer," Chemical Engineering, pp. 61-68 (November 28, 1952). This is residence time within the pump or line mixer itself. For a pump installed in an external line loop, the time required for circulating a volume equal to the tank contents is considered to be adequate for mixing of vessel contents. See Table 4-16. See fluid beds. Power consumption can be calculated from $P = \frac{m_{g} + m_{s}}{\rho_{g}}$, where $m_{g}$ is the gas flow rate, $\rho_{g}$ is the density, $m_{s}$ is the mixture, and $x$ is 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. All values include efficiency losses in drive and gears and correspond to the direct electricity or utility consumption. W. P. Wheland and W. E. Root, "Heat Transfer to Granular Solids in Agitated Units." Chem. Eng. Prog. 53, pp. 41-72 (1957)"
Table 2-2  Platt's Prices for Resid Fuel Oil (Five-Day Rolling Averages, September 14, 1993)

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

150,000 gal/batch = 368 ton/batch
Bacteria Culture

270,000 gal/batch = 307 ton/batch
Oil

1 ton/hr
Ca(OH)₂ or other (e.g. Biomass)

Motionless Mixer

pump1

1800 ton/hr

pump2

1030 ton/hr

270 ton/hr

Oil Phase

Aq. Phase (Bacteria Culture)

Oil Tank

Aq. Phase

53 ton/hr

Oil Phase

Sedimentation Centrifuge

61 ton/hr
Aq. Phase

Precipitation Drum

Filter

62 ton/hr

Aq. Phase (non-regulated)

Concentrated Sludge (metal hydroxide)
Figure 2-3 Ulrich's Fig. 5-61: Purchased Equipment Costs for Storage Vessels
Figure 2-4 Chemical Engineering (CE) Plant Cost Index for 1993-1994
Figure 2-5 Ulrich's Fig. 5-41: Purchased Equipment Costs for Motionless Mixers

![Graph showing purchased equipment cost for motionless mixers](image-url)

- **CE Plant Cost Index = 315 (mid-1982)**
- **Factors, \( F_{BM} \)**
  - Carbon steel: 1.5
  - Stainless steel: 2.9
  - Nickel alloy: 6.2
  - Titanium: 6.9
- **Equation:** \( C_{BM} = C_p \times F_{BM} \)

- **Diameter, \( D \) (m):**
  - 0.1
  - 1.0
Figure 2-6 Ulrich's Fig. 5-49: Purchased Equipment Costs for Pumps

![Chart showing purchased equipment costs for pumps with shaft power (kW) on the x-axis and purchased cost (electric motor drive included) on the y-axis. The chart includes lines for different types of pumps: centrifugal, reciprocating, and rotary positive displacement. Material factors for different materials such as cast iron, cast steel, copper, stainless steel, nickel, and titanium are also shown. The chart uses the formula $C_{BM} = C_P \times F_{BM}$ where $C_P$ is the purchased cost and $F_{BM}$ is the material factor.]
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
Figure 2-10 Ulrich's Fig. 5-42: Purchased Equipment Costs for Propeller and Turbine Agitators

\[ C_{BM} = C_P \times F_{BM} \]

Power consumption, \( P \) (kW)

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

\( C_{BM} \): Purchased equipment cost, \( C_P \): $
Figure 2-11  Ulrich's Fig. 5-57: Purchased Equipment Costs for Liquid Filters

![Graph showing the purchased equipment costs for liquid filter types with factors for different materials.](image-url)
Figure 2-12 Average Cost of NY Cargo Resid Fuel Oil
From Platt's September 14, 1993

\[ C = A + B \cdot S \]

- \[ A = 16.6455 \]
- \[ B = -2.0240 \]
Figure 2-13 Average Cost of NY Cargo Fuel Oil No.6 From Platt's Oilgram Price Report of September 14, 1993

\[ C = A + B \times S \]

\[ A = 23.0887 \]

\[ B = -1.4072 \]
Figure 2-14 US East Coast Spot No. 6 Oil Cargo Prices
(Bloomberg Oil Buyer's Guide 9/13/93)

\[ C = A + B \times S \]

- \( B = -2.3058 \)
- \( A = 16.9306 \)
Figure 2-15 Petroleos de Venezuela Official FOB Postings #6
Residual Fuels Prices (Bloomberg Oil Buyer's Guide 9/13/93)

Cost per Barrel, $C$

\[ C = A + B \cdot S \]

\[ A = 16.4232 \]

\[ B = -2.0628 \]
Figure 2-16 Estimated New York Contract Oil No.6 Cargo Prices
(Bloomberg Oil Buyer's Guide 9/13/93)

\[ C = A + B \cdot S \]

- \( B = -2.0055 \)
- \( A = 23.8449 \)

Cost per Barrel, \( C \) ($)

Amount of Sulfur, \( S \) (% wt)
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)

- Albany NY
  \[ A = 18.979 \quad B = -2.096 \]

- Boston MA
  \[ A = 21.139 \quad B = -2.165 \]

- Norfolk VA
  \[ A = 18.770 \quad B = -1.967 \]

- Baltimore MD
  \[ A = 20.370 \quad B = -2.320 \]

- Buffalo NY
  \[ A = 30.735 \quad B = -7.760 \]

\[ C = A + B \times S \]

Amount of Sulfur, S (% wt)

Cost per Barrel, C ($)

[Graph showing the relationship between cost per barrel and amount of sulfur for different locations, with equations and data points for each city.]
Figure 2-18 Northwest Europe Oil No.6 Cargo Prices

\[ C = A + B \cdot S \]

\[ B = -2.2722 \]

\[ A = 15.2250 \]
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)

Cost per Barrel, C ($)

Amount of Sulfur, S (% wt)

Boston MA
\[ A = 25.070 \quad B = -2.800 \]

New Haven CT
\[ A = 27.171 \quad B = -4.571 \]

\[ C = A + B \times S \]
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 $V = 1.33 \text{ m}^3$. The other end-point has coordinates $V = 1,535 \text{ m}^3$ 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

$$y = y_1 + \frac{y_2 - y_1}{x_2 - x_1}(x - x_1)$$

where

1. $x_1 = \log(V_1) = \log(1.33)$
2. $y_1 = \log(C_{p1}) = \log(2000)$
3. $x_2 = \log(V_2) = \log(1535)$
4. $y_2 = \log(C_{p2}) = \log(167880)$
5. $x = \log(V)$
6. $y = \log(C_p)$

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

$$C_p = 10^y$$

This procedure is implemented in a MS Excel spreadsheet and the calculation performed automatically. For example, let $V = 300 \text{ m}^3$. Therefore, from eqn. 3-1 it follows that:
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>
<thead>
<tr>
<th>Point #</th>
<th>D (m)</th>
<th>( C_p ) ($)</th>
<th>( x = \log(D) )</th>
<th>( y = \log(C_p) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0125</td>
<td>200.</td>
<td>-1.9031</td>
<td>2.30103</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>500.</td>
<td>-1.3010</td>
<td>2.69897</td>
</tr>
<tr>
<td>3</td>
<td>0.096</td>
<td>1000.</td>
<td>-1.0177</td>
<td>3.00000</td>
</tr>
<tr>
<td>4</td>
<td>0.2495</td>
<td>4000.</td>
<td>-0.6029</td>
<td>3.60206</td>
</tr>
<tr>
<td>5</td>
<td>0.55</td>
<td>15760.</td>
<td>-0.2596</td>
<td>4.19756</td>
</tr>
</tbody>
</table>

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

\[
L_i(x) = \prod_{j \neq i} \frac{(x - x_j)}{(x_i - x_j)}
\]  

(3-4)
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:

\[ L_2(x) = \frac{(x - x_1)(x - x_3)(x - x_4)}{(x_2 - x_1)(x_2 - x_3)(x_2 - x_4)} \quad (3-5) \]

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:

\[ P_1(x) = y_1L_1(x) + y_2L_2(x) + y_3L_3(x) + y_4L_4(x) \quad (3-6) \]

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 in 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

\[ L'_3(x) = \frac{(x - x_2)(x - x_4)(x - x_5)}{(x_3 - x_2)(x_3 - x_4)(x_3 - x_5)} \quad (3-7) \]

and \( P_2(x) \) is

\[ P_2(x) = y_2L'_2(x) + y_3L'_3(x) + y_4L'_4(x) + y_5L'_5(x) \quad (3-8) \]

\( P_2(x) \) 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 \( D = 0.5 \text{ m} \). 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 \( C_p = $13,264 \).

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)

\[ Cp = CP(ws) \]
Figure 3-4 Computerized Empirical Functional Relationship
"Material x Pressure Factor," MPF(Fp x Fm) 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, \(F_p\), for
Centrifugal Pumps, to Suction Pressure, \(pi\) (Ulrich Figure 5-50)
### Table 3-2 Computerized Cost Estimation of Biochemical Upgrading of Heavy Crudes

<table>
<thead>
<tr>
<th>Battery Limit Process Equipment Costs (BLE)</th>
<th>BLE= $793,840</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Oil Tank</strong></td>
<td>CBM= $93,359</td>
</tr>
<tr>
<td>Oil to be treated per batch</td>
<td>250,000 gal</td>
</tr>
<tr>
<td>Volumetric ratio bact/oil</td>
<td>rV= 0.60</td>
</tr>
<tr>
<td>Bacteria culture per batch</td>
<td>150,000 gal</td>
</tr>
<tr>
<td>Total reaction medium</td>
<td>400,001 gal</td>
</tr>
<tr>
<td>Fraction of tank normally used</td>
<td>0.8</td>
</tr>
<tr>
<td>Volume of oil tank (gal)</td>
<td>500,001 gal</td>
</tr>
<tr>
<td>Volume of oil tank (m³)</td>
<td>1892.71 m³</td>
</tr>
<tr>
<td>Cp (purchase cost)</td>
<td>Cp= $43,090</td>
</tr>
<tr>
<td>Installation factor (carbon steel)</td>
<td>FBM= 1.9</td>
</tr>
<tr>
<td>Bare module capital cost (1982)</td>
<td>CBM= $81,871</td>
</tr>
<tr>
<td>Factor to calc. cost at mid. 1993</td>
<td>1.1403</td>
</tr>
<tr>
<td>Bare module capital cost (1993)</td>
<td>CBM= $93,359</td>
</tr>
</tbody>
</table>

| **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)

<table>
<thead>
<tr>
<th>5 Sedimentation Centrifuge</th>
<th>CBM = $328,658</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate</td>
<td>m = 144 ton/hr</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>m = 40 kg/s</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>sp.gr. = 0.89</td>
</tr>
<tr>
<td>Volumetric flow rate</td>
<td>q = 0.045 m³/s</td>
</tr>
<tr>
<td>Cp (purchase cost)</td>
<td>Cp = $144,108</td>
</tr>
<tr>
<td>Installation factor (carbon steel)</td>
<td>FBM = 2</td>
</tr>
<tr>
<td>Bare module capital cost (1982)</td>
<td>CBM = $288,216</td>
</tr>
<tr>
<td>Bare module capital cost (1993)</td>
<td>CBM = $328,658</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6 Precipitation Drum</th>
<th>CBM = $137,540</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel volume</td>
<td>V = 50,000 gal</td>
</tr>
<tr>
<td>Vessel volume</td>
<td>V = 189.27 m³</td>
</tr>
<tr>
<td>Purchase cost</td>
<td>Cp = $45,068</td>
</tr>
<tr>
<td>Installation factor, carbon steel</td>
<td>FBM = 1.9</td>
</tr>
<tr>
<td>Bare module capital cost (1982)</td>
<td>CBM = $85,630</td>
</tr>
<tr>
<td>Bare module capital cost (1993)</td>
<td>CBM = $97,645</td>
</tr>
</tbody>
</table>

- Agitator power (0.2V×0.8) | P = 13.3 kW |
- Cp (purchase cost)         | Cp = $13,994 |
- Installation factor (stainless steel) | FBM = 2.5 |
- Bare module capital cost (1982) | CBM = $34,986 |
- Bare module capital cost (1993) | CBM = $39,895 |

<table>
<thead>
<tr>
<th>7 Filter Press</th>
<th>CBM = $29,234</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter area</td>
<td>A = 10 m²</td>
</tr>
<tr>
<td>Cp (purchase cost)</td>
<td>Cp = $7,325</td>
</tr>
<tr>
<td>Installation factor (polypropylene)</td>
<td>FBM = 3.5</td>
</tr>
<tr>
<td>Bare module capital cost (1982)</td>
<td>CBM = $25,637</td>
</tr>
<tr>
<td>Bare module capital cost (1993)</td>
<td>CBM = $29,234</td>
</tr>
</tbody>
</table>
Table 3-3 Additional Input Values and Intermediate Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery limit process equip.</td>
<td>BLE = $793,840</td>
</tr>
<tr>
<td>Electric cost rate</td>
<td>0.05 $/kWh</td>
</tr>
<tr>
<td>Average motor efficiencies</td>
<td>0.8</td>
</tr>
<tr>
<td>Electric power for pumps</td>
<td>60.3 kW</td>
</tr>
<tr>
<td>Power for centrifuge &amp; prec. drum</td>
<td>20.8 kW</td>
</tr>
<tr>
<td>Stream days in a year</td>
<td>330 sd/yr</td>
</tr>
<tr>
<td>Working hours in a year</td>
<td>7,920 hours/yr</td>
</tr>
<tr>
<td>Light. power (fraction of total power)</td>
<td>3%</td>
</tr>
<tr>
<td>Utilities cost</td>
<td>UT = $20,491</td>
</tr>
<tr>
<td>General facilities</td>
<td>GF = $277,844</td>
</tr>
<tr>
<td>Total facilities costs</td>
<td>TFC = $1,092,175</td>
</tr>
<tr>
<td>Engineering &amp; home offices</td>
<td>E&amp;HO = $109,217</td>
</tr>
<tr>
<td>Plant startup and minor revamp</td>
<td>PSU = $54,609</td>
</tr>
<tr>
<td>Process royalties</td>
<td>PR = $21,843</td>
</tr>
<tr>
<td>Number of batch cycles</td>
<td>50</td>
</tr>
<tr>
<td>Total mass of batch</td>
<td>1325 ton</td>
</tr>
<tr>
<td>Duration per batch cycle</td>
<td>36.8 hours</td>
</tr>
<tr>
<td>Duration of product process</td>
<td>9.2 hours</td>
</tr>
<tr>
<td>Set up time</td>
<td>2.0 hours</td>
</tr>
<tr>
<td>Time duration of a batch</td>
<td>48.0 hours</td>
</tr>
<tr>
<td>Number of batches in a year</td>
<td>165.0 batches/yr</td>
</tr>
<tr>
<td>Crude oil consumed per year</td>
<td>982,142.86 bbl/yr</td>
</tr>
<tr>
<td>Sulfur in crude</td>
<td>3.00% wt%</td>
</tr>
<tr>
<td>Cost of crude per barrel</td>
<td>10.574 $/bbl</td>
</tr>
<tr>
<td>Feed per st. day of crude oil</td>
<td>FEED = $31,469 $/day</td>
</tr>
<tr>
<td>Working capital</td>
<td>WC = $640,301</td>
</tr>
<tr>
<td>Price of bacteria culture</td>
<td>10 $/m³</td>
</tr>
<tr>
<td>Number of employees at a time</td>
<td>2</td>
</tr>
<tr>
<td>Labor/(plant oper.-year)</td>
<td>$280,670</td>
</tr>
<tr>
<td>Total capital invest. cost</td>
<td>TCIC = $1,918,145</td>
</tr>
<tr>
<td>Sulfur removed (% of initial)</td>
<td>33.33%</td>
</tr>
<tr>
<td>Sulfur removed (% of crude wt)</td>
<td>1.00%</td>
</tr>
<tr>
<td>Sulfur sale value</td>
<td>50.00 $/lt</td>
</tr>
<tr>
<td>Sulfur sale value</td>
<td>49.21 $/1000kg</td>
</tr>
<tr>
<td>Sulfur in processed oil</td>
<td>2.00% wt%</td>
</tr>
<tr>
<td>Value of processed oil</td>
<td>12.598 $/bbl</td>
</tr>
<tr>
<td>Weight of sulfur removed year</td>
<td>1249.0 ton/yr</td>
</tr>
<tr>
<td>Crude type and date of cost</td>
<td>Resid Sep 93</td>
</tr>
<tr>
<td>Crude cost intercept</td>
<td>A = 16.6455</td>
</tr>
<tr>
<td>Slope of cost [C = A + B*S]</td>
<td>B = -2.0239905</td>
</tr>
</tbody>
</table>
Table 3-4 Summary of Operating Costs and Net Realization

<table>
<thead>
<tr>
<th>Operating Costs</th>
<th>$/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>FEEDA= $10,384,761</td>
</tr>
<tr>
<td>Utilities</td>
<td>UT= $20,491</td>
</tr>
<tr>
<td>Catalysts</td>
<td>CAT= $936,889</td>
</tr>
<tr>
<td>Labor</td>
<td>LB= $561,340</td>
</tr>
<tr>
<td>Maintenance</td>
<td>MT= $38,363</td>
</tr>
<tr>
<td>Overhead, prop tax, insur.</td>
<td>[OH+PT+IN]= $50,240</td>
</tr>
<tr>
<td>Capital charges</td>
<td>OC= $383,629</td>
</tr>
<tr>
<td></td>
<td>Total Operating Costs OC= $12,375,713</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Byproduct Credits</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenues from oil</td>
<td>OPC= $12,372,609</td>
</tr>
<tr>
<td>Sulfur credit</td>
<td>BPC= $61,469</td>
</tr>
<tr>
<td></td>
<td>Total Credits CR= $12,434,078</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NET REALIZATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NR= $58,365</td>
</tr>
<tr>
<td></td>
<td>NR/bbl= $0.059</td>
</tr>
</tbody>
</table>

3-18
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...
4. Economic Sensitivity Analysis

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.

\[ \% \text{ Change NR/bbl} = \frac{NR_{\text{new}}-NR_{\text{base}}}{|NR_{\text{base}}|} \times 100 \]  

(4-1)

where \( NR_{\text{base}} \) is the net realization per barrel computed with the base values, \( NR_{\text{new}} \) 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 \( NR_{\text{base}} \). 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 $C = A + BS$, 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 $\Delta C = -rB * S_i$, 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 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
4. Economic Sensitivity Analysis

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

\[ C = A + B \cdot S \] (4-2)
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:

$$r = \frac{S_f - S_i}{S_i} \quad (4-3)$$

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:

$$C_i = A + B* S_i \quad (4-4)$$

and:

$$C_f = A + B* S_f \quad (4-5)$$

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

$$\Delta C = B*(S_f - S_i) \quad (4-6)$$

from eqns. 4-6 and 4-3:

$$\Delta C = - r*B* S_i \quad (4-7)$$

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

4-6
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 2-7. 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, \( \Delta \), 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. \( \Delta C \) 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:

$$\text{NR/BBL} = A + B \times S/100$$  \hfill (4-8)

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, $C = A + B \times S$, 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)

NR/BBL = A + B*Cost

A = 1.0133
B = -0.0954

<table>
<thead>
<tr>
<th>Cost ($/m3)</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>$0.155</td>
<td>160.5</td>
</tr>
<tr>
<td>8</td>
<td>$0.250</td>
<td>321.0</td>
</tr>
<tr>
<td>7</td>
<td>$0.346</td>
<td>481.6</td>
</tr>
<tr>
<td>6</td>
<td>$0.441</td>
<td>642.1</td>
</tr>
<tr>
<td>5</td>
<td>$0.536</td>
<td>802.6</td>
</tr>
</tbody>
</table>

Bacterial Culture Cost, Cost ($/m3)
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)

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

$A = 1.0226$  
$B = -1.6054$  
$NR/BBL = A + B \cdot rv$
Figure 4.3 Effect of Variation of Total Batch Time on Net Realization
(All Other Parameters at the Base Case Values)

\[ NR/BBL = A + B \cdot T \]

\[ A = 0.9971 \]

\[ B = -0.0195 \]

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>$0.059$</td>
<td>0.0</td>
</tr>
<tr>
<td>45</td>
<td>$0.118$</td>
<td>98.6</td>
</tr>
<tr>
<td>42</td>
<td>$0.177$</td>
<td>197.2</td>
</tr>
<tr>
<td>39</td>
<td>$0.235$</td>
<td>295.9</td>
</tr>
<tr>
<td>36</td>
<td>$0.294$</td>
<td>394.5</td>
</tr>
<tr>
<td>33</td>
<td>$0.352$</td>
<td>493.1</td>
</tr>
</tbody>
</table>
Figure 4.4 Effect of Variation of Total Batch Time and Bacterial Cost on Net Realization (All Other Parameters at the Base Case Values)

<table>
<thead>
<tr>
<th>Bacteria Cost ($/m^3)</th>
<th>Processing time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>$0.250</td>
</tr>
<tr>
<td>9</td>
<td>$0.155</td>
</tr>
<tr>
<td>10</td>
<td>$0.059</td>
</tr>
<tr>
<td>11</td>
<td>-$0.036</td>
</tr>
<tr>
<td>12</td>
<td>-$0.131</td>
</tr>
<tr>
<td>13</td>
<td>-$0.227</td>
</tr>
<tr>
<td>14</td>
<td>-$0.322</td>
</tr>
<tr>
<td>15</td>
<td>-$0.418</td>
</tr>
</tbody>
</table>
Figure 4.5 Effect of Variation of Sulfur in Feed on Net Realization
(All Other Parameters at the Base Case Values)

\[ NR/BBL = A + B \cdot S \]

\[ A = -2.1081 \]

\[ B = 72.2512 \]

<table>
<thead>
<tr>
<th>S Crude (%)</th>
<th>NR/BBL</th>
<th>S Product (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>$0.421</td>
<td>2.33</td>
</tr>
<tr>
<td>2.8</td>
<td>-$0.085</td>
<td>1.87</td>
</tr>
<tr>
<td>2.2</td>
<td>-$0.519</td>
<td>1.47</td>
</tr>
<tr>
<td>1.0</td>
<td>-$1.386</td>
<td>0.67</td>
</tr>
<tr>
<td>0.5</td>
<td>-$1.747</td>
<td>0.33</td>
</tr>
<tr>
<td>0.3</td>
<td>-$1.891</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Figure 4.6 Effect of Variation of Number of Operators on Net Realization
(All Other Parameters at the Base Case Values)

Net Realization per BBL, NR/BBL ($/BBL)

NR/BBL = A + B*Nop

A = 0.6310
B = -0.2858

<table>
<thead>
<tr>
<th>Operators</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.345</td>
<td>480.9</td>
</tr>
<tr>
<td>1.5</td>
<td>$0.202</td>
<td>240.4</td>
</tr>
<tr>
<td>2</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>2.5</td>
<td>-$0.083</td>
<td>-240.4</td>
</tr>
<tr>
<td>3</td>
<td>-$0.226</td>
<td>-480.9</td>
</tr>
<tr>
<td>3.5</td>
<td>-$0.369</td>
<td>-721.3</td>
</tr>
</tbody>
</table>

Number of Operators, Nop
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)

<table>
<thead>
<tr>
<th>Amount of Oil per Batch, (gal)</th>
<th>Net Realization per BBL, NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>200,000</td>
<td>$0.167</td>
<td>381.4</td>
</tr>
<tr>
<td>250,000</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>300,000</td>
<td>$0.211</td>
<td>254.7</td>
</tr>
<tr>
<td>350,000</td>
<td>$0.319</td>
<td>436.9</td>
</tr>
<tr>
<td>400,000</td>
<td>$0.400</td>
<td>573.7</td>
</tr>
<tr>
<td>450,000</td>
<td>$0.464</td>
<td>680.3</td>
</tr>
</tbody>
</table>

48 hr fixed, NR/BBL
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)

<table>
<thead>
<tr>
<th>Amount of Oil per Batch, Voil (gal)</th>
<th>Net Realization per BBL, NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>200,000</td>
<td>$0.056</td>
<td>-5.8</td>
</tr>
<tr>
<td>250,000</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>300,000</td>
<td>$0.060</td>
<td>1.1</td>
</tr>
<tr>
<td>350,000</td>
<td>$0.059</td>
<td>-0.3</td>
</tr>
<tr>
<td>400,000</td>
<td>$0.058</td>
<td>-3.2</td>
</tr>
<tr>
<td>450,000</td>
<td>$0.055</td>
<td>-7.1</td>
</tr>
</tbody>
</table>
Figure 4.9 Effect of Variation of Number of Cycles on Net Realization (All Other Parameters at the Base Case Values)

\[ NR/BBL = A + B\cdot Nc \]

\[ A = 0.7783 \]

\[ B = -0.0144 \]

<table>
<thead>
<tr>
<th>No cycles</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$0.347</td>
<td>483.9</td>
</tr>
<tr>
<td>35</td>
<td>$0.275</td>
<td>362.9</td>
</tr>
<tr>
<td>40</td>
<td>$0.203</td>
<td>241.9</td>
</tr>
<tr>
<td>45</td>
<td>$0.131</td>
<td>121.0</td>
</tr>
<tr>
<td>50</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>55</td>
<td>-$0.012</td>
<td>-121.0</td>
</tr>
</tbody>
</table>
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)

Fixed Number of Cycles per Batch = 50

Mass flow rate of pumps 1 and 2 are the base values multiplied by flow factor

<table>
<thead>
<tr>
<th>Flow Factor</th>
<th>50 Cycles</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90</td>
<td>-$0.016</td>
<td>-126.7</td>
</tr>
<tr>
<td>1.00</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>1.10</td>
<td>$0.121</td>
<td>103.6</td>
</tr>
<tr>
<td>1.20</td>
<td>$0.172</td>
<td>190.0</td>
</tr>
<tr>
<td>1.30</td>
<td>$0.216</td>
<td>263.0</td>
</tr>
<tr>
<td>1.40</td>
<td>$0.253</td>
<td>325.6</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>B</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>-$1.006</td>
<td>-1792.1</td>
</tr>
<tr>
<td>-1.5</td>
<td>-$0.486</td>
<td>-917.0</td>
</tr>
<tr>
<td>-2</td>
<td>$0.034</td>
<td>-42.0</td>
</tr>
<tr>
<td>-2.5</td>
<td>$0.554</td>
<td>833.1</td>
</tr>
<tr>
<td>-3</td>
<td>$1.074</td>
<td>1708.1</td>
</tr>
<tr>
<td>-3.5</td>
<td>$1.594</td>
<td>2583.1</td>
</tr>
</tbody>
</table>

Net Realization per BBL, NR/BBL ($/BBL)

Slope of Curve "Feed Cost vs Sulfur Content," B

\[ NR/BBL = a + b \times B \]

- \( a = -2.0455 \)
- \( b = -1.0400 \)
4. Economic Sensitivity Analysis

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)

*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)

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

A = -2.0272

B = 6.2597

NR/BBL = A + B*ΔS/S

Sulfur Reduction per Batch, ΔS/S (%)
Figure 4.14 Effect of Variation of Flow Rate Into The Centrifuge on Net Realization (All Other Parameters at the Base Case Values)

<table>
<thead>
<tr>
<th>Flow Rate</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>$0.052</td>
<td>-13.2</td>
</tr>
<tr>
<td>144</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>152</td>
<td>$0.065</td>
<td>10.1</td>
</tr>
<tr>
<td>158</td>
<td>$0.069</td>
<td>16.9</td>
</tr>
</tbody>
</table>
Figure 4.15 Effect of Variation of Pumps No.1 & No.2 Efficiency on Net Realization (All Other Parameters at the Base Case Values)

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>$0.051</td>
<td>-13.9</td>
</tr>
<tr>
<td>0.6</td>
<td>$0.059</td>
<td>0.0</td>
</tr>
<tr>
<td>0.7</td>
<td>$0.066</td>
<td>10.2</td>
</tr>
<tr>
<td>0.8</td>
<td>$0.070</td>
<td>18.2</td>
</tr>
<tr>
<td>0.9</td>
<td>$0.074</td>
<td>24.5</td>
</tr>
</tbody>
</table>
### 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)

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

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Base value</th>
<th>New Value</th>
<th>($)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur in crude</td>
<td>2.80%</td>
<td>3.08%</td>
<td>-0.627</td>
<td>+18.5</td>
</tr>
<tr>
<td>Sulfur removed (% of initial)</td>
<td>33.33%</td>
<td>36.67%</td>
<td>-0.633</td>
<td>+17.8</td>
</tr>
<tr>
<td>Crude cost slope (B)</td>
<td>-1.4072</td>
<td>-1.5479</td>
<td>-0.633</td>
<td>+17.7</td>
</tr>
<tr>
<td>Bacteria cult. vol. ratio (rv)</td>
<td>0.60</td>
<td>0.54</td>
<td>-0.673</td>
<td>+12.5</td>
</tr>
<tr>
<td>Price of bacteria ($/m^3)</td>
<td>$10.00</td>
<td>$9.00</td>
<td>-0.674</td>
<td>+12.4</td>
</tr>
<tr>
<td>Batch processing time (hr)</td>
<td>48</td>
<td>43.2</td>
<td>-0.676</td>
<td>+12.2</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fixed time)</td>
<td>250,000</td>
<td>275,000</td>
<td>-0.687</td>
<td>+10.7</td>
</tr>
<tr>
<td>Number of batch cycles</td>
<td>50</td>
<td>45</td>
<td>-0.698</td>
<td>+9.3</td>
</tr>
<tr>
<td>Pump mass flow factor (fix cycles)</td>
<td>1</td>
<td>1.1</td>
<td>-0.708</td>
<td>+8.0</td>
</tr>
<tr>
<td>No. of employees at a time</td>
<td>2.0</td>
<td>1.8</td>
<td>-0.713</td>
<td>+7.4</td>
</tr>
<tr>
<td>Stream days in a year</td>
<td>330</td>
<td>363</td>
<td>-0.716</td>
<td>+7.0</td>
</tr>
<tr>
<td>Specific gravity of crude</td>
<td>0.80</td>
<td>0.88</td>
<td>-0.758</td>
<td>+1.5</td>
</tr>
<tr>
<td>Solution flow rate into centrifuge</td>
<td>144</td>
<td>158.4</td>
<td>-0.759</td>
<td>+1.3</td>
</tr>
<tr>
<td>Sulfur sale value ($/lt)</td>
<td>$50.00</td>
<td>$55.00</td>
<td>-0.764</td>
<td>+0.8</td>
</tr>
<tr>
<td>Pump efficiencies</td>
<td>0.6</td>
<td>0.66</td>
<td>-0.766</td>
<td>+0.5</td>
</tr>
<tr>
<td>Diameter of motionless mixer</td>
<td>0.5</td>
<td>0.45</td>
<td>-0.766</td>
<td>+0.5</td>
</tr>
<tr>
<td>Electric. cost rate ($/kWh)</td>
<td>$0.05</td>
<td>$0.045</td>
<td>-0.767</td>
<td>+0.4</td>
</tr>
<tr>
<td>Fraction of tank used</td>
<td>0.8</td>
<td>0.88</td>
<td>-0.767</td>
<td>+0.3</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fix cycles)</td>
<td>250,000</td>
<td>275,000</td>
<td>-0.769</td>
<td>+0.3</td>
</tr>
</tbody>
</table>
### Table 4-3 Effect of Variation of Bacterial Culture Cost on NR (Fuel Oil #6, 2.8% S)

<table>
<thead>
<tr>
<th>Bacterial Cost ($/m³)</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>-$0.674</td>
<td>12.4</td>
</tr>
<tr>
<td>8</td>
<td>-$0.579</td>
<td>24.8</td>
</tr>
<tr>
<td>7</td>
<td>-$0.484</td>
<td>37.2</td>
</tr>
<tr>
<td>6</td>
<td>-$0.388</td>
<td>49.6</td>
</tr>
<tr>
<td>5</td>
<td>-$0.293</td>
<td>62.0</td>
</tr>
</tbody>
</table>

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

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

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

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>45</td>
<td>-$0.711</td>
<td>7.6</td>
</tr>
<tr>
<td>42</td>
<td>-$0.653</td>
<td>15.2</td>
</tr>
<tr>
<td>39</td>
<td>-$0.594</td>
<td>22.8</td>
</tr>
<tr>
<td>36</td>
<td>-$0.535</td>
<td>30.5</td>
</tr>
<tr>
<td>33</td>
<td>-$0.477</td>
<td>38.1</td>
</tr>
</tbody>
</table>
### Table 4-6 Effect of Variation of Total Batch Time and Bacterial Culture Cost on Net Realization (Fuel Oil #6, 2.8% S)

<table>
<thead>
<tr>
<th>Bacteria Cost $/m3</th>
<th>Processing time (hr)</th>
<th>48</th>
<th>45</th>
<th>42</th>
<th>39</th>
<th>36</th>
<th>33</th>
<th>30</th>
<th>27</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>-$0.579</td>
<td>-$0.520</td>
<td>-$0.462</td>
<td>-$0.403</td>
<td>-$0.345</td>
<td>-$0.286</td>
<td>-$0.227</td>
<td>-$0.169</td>
<td>-$0.110</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-$0.674</td>
<td>-$0.616</td>
<td>-$0.557</td>
<td>-$0.499</td>
<td>-$0.440</td>
<td>-$0.381</td>
<td>-$0.323</td>
<td>-$0.264</td>
<td>-$0.205</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-$0.770</td>
<td>-$0.711</td>
<td>-$0.653</td>
<td>-$0.594</td>
<td>-$0.535</td>
<td>-$0.477</td>
<td>-$0.418</td>
<td>-$0.359</td>
<td>-$0.301</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-$0.865</td>
<td>-$0.807</td>
<td>-$0.748</td>
<td>-$0.689</td>
<td>-$0.631</td>
<td>-$0.572</td>
<td>-$0.513</td>
<td>-$0.455</td>
<td>-$0.396</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-$0.961</td>
<td>-$0.902</td>
<td>-$0.843</td>
<td>-$0.785</td>
<td>-$0.726</td>
<td>-$0.667</td>
<td>-$0.609</td>
<td>-$0.550</td>
<td>-$0.492</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-$1.056</td>
<td>-$1.097</td>
<td>-$0.939</td>
<td>-$0.880</td>
<td>-$0.821</td>
<td>-$0.763</td>
<td>-$0.704</td>
<td>-$0.646</td>
<td>-$0.587</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>-$1.151</td>
<td>-$1.034</td>
<td>-$0.975</td>
<td>-$0.917</td>
<td>-$0.858</td>
<td>-$0.800</td>
<td>-$0.741</td>
<td>-$0.682</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-$1.247</td>
<td>-$1.188</td>
<td>-$1.129</td>
<td>-$1.071</td>
<td>-$1.012</td>
<td>-$0.954</td>
<td>-$0.895</td>
<td>-$0.836</td>
<td>-$0.778</td>
<td></td>
</tr>
</tbody>
</table>
### 4. Economic Sensitivity Analysis

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

<table>
<thead>
<tr>
<th>%S Feed</th>
<th>NR/BBL</th>
<th>%S Prod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>-$0.414</td>
<td>2.3</td>
</tr>
<tr>
<td>2.8</td>
<td>-$0.770</td>
<td>1.9</td>
</tr>
<tr>
<td>2.2</td>
<td>-$1.075</td>
<td>1.5</td>
</tr>
<tr>
<td>1.0</td>
<td>-$1.685</td>
<td>0.7</td>
</tr>
<tr>
<td>0.5</td>
<td>-$1.940</td>
<td>0.3</td>
</tr>
<tr>
<td>0.3</td>
<td>-$2.041</td>
<td>0.2</td>
</tr>
</tbody>
</table>

#### Table 4-8 Effect of Variation of Number of Operators on NR (Fuel Oil #6, 2.8% S)

<table>
<thead>
<tr>
<th>No. of Operators</th>
<th>NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>($0.484)</td>
<td>37.1</td>
</tr>
<tr>
<td>1.5</td>
<td>-$0.627</td>
<td>18.6</td>
</tr>
<tr>
<td>2</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>2.5</td>
<td>-$0.913</td>
<td>-18.6</td>
</tr>
<tr>
<td>3</td>
<td>-$1.055</td>
<td>-37.1</td>
</tr>
<tr>
<td>3.5</td>
<td>-$1.198</td>
<td>-55.7</td>
</tr>
</tbody>
</table>

#### Table 4-9 Effect of Variation of Amount of Oil per Batch on NR at Fixed Batch Time

<table>
<thead>
<tr>
<th>Feed Oil (gal)</th>
<th>48 hr fix NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>200,000</td>
<td>-$0.996</td>
<td>-29.4</td>
</tr>
<tr>
<td>250,000</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>300,000</td>
<td>-$0.618</td>
<td>19.7</td>
</tr>
<tr>
<td>350,000</td>
<td>-$0.510</td>
<td>33.7</td>
</tr>
<tr>
<td>400,000</td>
<td>-$0.429</td>
<td>44.3</td>
</tr>
<tr>
<td>450,000</td>
<td>-$0.365</td>
<td>52.5</td>
</tr>
</tbody>
</table>

#### Table 4-10 Effect of Variation of Amount of Oil per Batch on NR at Fixed Batch Cycles

<table>
<thead>
<tr>
<th>Feed Oil (gal)</th>
<th>50 Cycles NR/BBL</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>200,000</td>
<td>-$0.773</td>
<td>-0.4</td>
</tr>
<tr>
<td>250,000</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>300,000</td>
<td>-$0.769</td>
<td>0.1</td>
</tr>
<tr>
<td>350,000</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>400,000</td>
<td>-$0.772</td>
<td>-0.2</td>
</tr>
<tr>
<td>450,000</td>
<td>-$0.774</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
Table 4-11 Effect of Variation of Number of Cycles on NR (Fuel Oil #6, 2.8% S)

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$-0.482</td>
<td>37.4</td>
</tr>
<tr>
<td>35</td>
<td>$-0.554</td>
<td>28.0</td>
</tr>
<tr>
<td>40</td>
<td>$-0.626</td>
<td>18.7</td>
</tr>
<tr>
<td>45</td>
<td>$-0.698</td>
<td>9.3</td>
</tr>
<tr>
<td>50</td>
<td>$-0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>55</td>
<td>$-0.842</td>
<td>-9.3</td>
</tr>
</tbody>
</table>

Table 4-12 Effect of Variation of Flow Rates in Pumps No.1 & No.2 on NR (Fuel Oil #6, 2.8% S)

<table>
<thead>
<tr>
<th>Flow Factor</th>
<th>50 Cycles NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90</td>
<td>$-0.845</td>
<td>-9.8</td>
</tr>
<tr>
<td>1.00</td>
<td>$-0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>1.10</td>
<td>$-0.708</td>
<td>8.0</td>
</tr>
<tr>
<td>1.20</td>
<td>$-0.657</td>
<td>14.7</td>
</tr>
<tr>
<td>1.30</td>
<td>$-0.613</td>
<td>20.3</td>
</tr>
<tr>
<td>1.40</td>
<td>$-0.576</td>
<td>25.1</td>
</tr>
</tbody>
</table>

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”

<table>
<thead>
<tr>
<th>B</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.00</td>
<td>$1.165</td>
<td>51.3</td>
</tr>
<tr>
<td>-1.50</td>
<td>$0.680</td>
<td>11.7</td>
</tr>
<tr>
<td>-2.00</td>
<td>$0.194</td>
<td>74.8</td>
</tr>
<tr>
<td>-2.50</td>
<td>$0.291</td>
<td>137.8</td>
</tr>
<tr>
<td>-3.00</td>
<td>$0.776</td>
<td>200.9</td>
</tr>
<tr>
<td>-3.50</td>
<td>$1.262</td>
<td>263.9</td>
</tr>
</tbody>
</table>
4. Economic Sensitivity Analysis

Table 4-14 Effect of Variation of the Intercept of Curve "Feed Cost vs Sulfur Content"

<table>
<thead>
<tr>
<th>A</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.00</td>
<td>-$0.662</td>
<td>14.0</td>
</tr>
<tr>
<td>17.50</td>
<td>-$0.695</td>
<td>9.7</td>
</tr>
<tr>
<td>20.00</td>
<td>-$0.729</td>
<td>5.4</td>
</tr>
<tr>
<td>22.50</td>
<td>-$0.762</td>
<td>1.0</td>
</tr>
<tr>
<td>25.00</td>
<td>-$0.795</td>
<td>-3.3</td>
</tr>
<tr>
<td>27.50</td>
<td>-$0.829</td>
<td>-7.6</td>
</tr>
</tbody>
</table>

Table 4-15 Effect of Variation of Sulfur Reduction per Batch on NR (Fuel Oil #6)

<table>
<thead>
<tr>
<th>S reduction</th>
<th>$-0.769716</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>-$0.907</td>
<td>-17.8</td>
</tr>
<tr>
<td>33%</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>40%</td>
<td>-$0.495</td>
<td>35.6</td>
</tr>
<tr>
<td>50%</td>
<td>-$0.084</td>
<td>89.1</td>
</tr>
<tr>
<td>60%</td>
<td>$0.328</td>
<td>142.6</td>
</tr>
<tr>
<td>70%</td>
<td>$0.739</td>
<td>196.0</td>
</tr>
<tr>
<td>80%</td>
<td>$1.151</td>
<td>249.5</td>
</tr>
</tbody>
</table>

Table 4-16 Effect of Variation of Flow Rate into Centrifuge on NR

<table>
<thead>
<tr>
<th>Feed Oil (gal)</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>135.00</td>
<td>-$0.778</td>
<td>-1.0</td>
</tr>
<tr>
<td>144.00</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>152.00</td>
<td>-$0.764</td>
<td>0.8</td>
</tr>
<tr>
<td>158.00</td>
<td>-$0.760</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 4-17 Effect of Variation of Pumps No.1 & No.2 Efficiency on NR

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>NR/BBL</th>
<th>%Change NR/BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>-$0.778</td>
<td>-1.1</td>
</tr>
<tr>
<td>0.60</td>
<td>-$0.770</td>
<td>0.0</td>
</tr>
<tr>
<td>0.70</td>
<td>-$0.764</td>
<td>0.8</td>
</tr>
<tr>
<td>0.80</td>
<td>-$0.759</td>
<td>1.4</td>
</tr>
<tr>
<td>0.90</td>
<td>-$0.755</td>
<td>1.9</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Source</th>
<th>Feed % wt S</th>
<th>2.8%</th>
<th>2.2%</th>
<th>2.0%</th>
<th>1.0%</th>
<th>0.70%</th>
<th>0.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>US East Coast Spot No.6 Oil Cargo Prices</td>
<td>NR/BBL</td>
<td>$0.185</td>
<td>-$0.307</td>
<td>-$0.471</td>
<td>-$1.292</td>
<td>-$1.538</td>
<td>-$1.702</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>82.021</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.112</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroles de Venezuela Official FOB Postings #6 Residual Fuel Prices</td>
<td>Feed % wt S</td>
<td>2.8%</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.0%</td>
<td>0.70%</td>
<td>0.50%</td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.044</td>
<td>-$0.486</td>
<td>-$0.633</td>
<td>-$1.369</td>
<td>-$1.590</td>
<td>-$1.737</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>73.595</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.105</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated New York Contract Oil No.6 Cargo Prices</td>
<td>Feed % wt S</td>
<td>2.8%</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.0%</td>
<td>0.70%</td>
<td>0.50%</td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.199</td>
<td>-$0.629</td>
<td>-$0.772</td>
<td>-$1.488</td>
<td>-$1.703</td>
<td>-$1.846</td>
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<tr>
<td></td>
<td>B</td>
<td>71.609</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.204</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Prices of US East Coast Residual Fuel Oil No. 6</td>
<td>Feed % wt S</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumer Tankcar, FOB Supplier’s Rack</td>
<td>NR/BBL</td>
<td>-$0.495</td>
<td>-$0.644</td>
<td>-$1.018</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>74.753</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.139</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albany NY</td>
<td>Feed % wt S</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.471</td>
<td>-$1.011</td>
<td>-$1.397</td>
<td></td>
<td></td>
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<td></td>
<td>B</td>
<td>71.144</td>
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</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.168</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boston MA</td>
<td>Feed % wt S</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.450</td>
<td>-$0.661</td>
<td>-$1.082</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>70.264</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.136</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Norfolk VA</td>
<td>Feed % wt S</td>
<td>2.4%</td>
<td>2.1%</td>
<td>1.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.508</td>
<td>-$0.920</td>
<td>-$1.333</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>82.513</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.158</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baltimore MD</td>
<td>Feed % wt S</td>
<td>2.00%</td>
<td>1.50%</td>
<td>1.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>-$0.508</td>
<td>-$0.920</td>
<td>-$1.333</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>82.513</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.158</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffalo NY</td>
<td>Feed % wt S</td>
<td>1.50%</td>
<td>1.30%</td>
<td>1.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR/BBL</td>
<td>$1.765</td>
<td>$1.224</td>
<td>$0.682</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>270.753</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>-2.296</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B*(%S/100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Feed %wt S</th>
<th>3.0%</th>
<th>2.5%</th>
<th>1.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWBBL</td>
<td>$0.336</td>
<td>-$0.068</td>
<td>-$0.876</td>
</tr>
<tr>
<td>A</td>
<td>-2.089</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B'(%S/100)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Northwest Europe Oil No.6 Cargo Prices**

**US Coast Residual Fuel Oil No.4**

**Consumer Tankcar, FOB Supplier's Rack Average Prices**

<table>
<thead>
<tr>
<th>Boston MA</th>
<th>1.00%</th>
<th>0.75%</th>
<th>0.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWBBL</td>
<td>-$1.229</td>
<td>-$1.477</td>
<td>-$1.446</td>
</tr>
<tr>
<td>B</td>
<td>99.153</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-2.220</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B'(%S/100)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New Haven CT</th>
<th>1.00%</th>
<th>0.50%</th>
<th>0.75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWBBL</td>
<td>-$0.643</td>
<td>-$1.446</td>
<td>-$0.624</td>
</tr>
<tr>
<td>B</td>
<td>160.562</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-2.248</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWBBL = A + B'(%S/100)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Base value</th>
<th>New Value</th>
<th>Cumulative New NR $/bbl</th>
<th>Add. % Increase NR/$bbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur in feed</td>
<td>3.00%</td>
<td>3.15%</td>
<td>0.168</td>
<td>162.4</td>
</tr>
<tr>
<td>Sulfur removed (% of initial)</td>
<td>33.33%</td>
<td>35.00%</td>
<td>0.277</td>
<td>65.3</td>
</tr>
<tr>
<td>Bacteria cult./oil feed vol. ratio (nv)</td>
<td>0.60</td>
<td>0.57</td>
<td>0.325</td>
<td>17.4</td>
</tr>
<tr>
<td>Price of bacteria ($/m3)</td>
<td>$10.00</td>
<td>$9.50</td>
<td>0.371</td>
<td>13.9</td>
</tr>
<tr>
<td>Batch processing time (hr)</td>
<td>48</td>
<td>45.6</td>
<td>0.418</td>
<td>12.6</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fixed time)</td>
<td>250,000</td>
<td>262,500</td>
<td>0.459</td>
<td>9.8</td>
</tr>
<tr>
<td>No. of employees at a time</td>
<td>2</td>
<td>1.9</td>
<td>0.485</td>
<td>5.6</td>
</tr>
<tr>
<td>Stream days in a year</td>
<td>330</td>
<td>346.5</td>
<td>0.506</td>
<td>4.3</td>
</tr>
<tr>
<td>Specific gravity of feed</td>
<td>0.80</td>
<td>0.84</td>
<td>0.511</td>
<td>1.2</td>
</tr>
<tr>
<td>Sulfur sale value ($/t)</td>
<td>$50.00</td>
<td>$52.50</td>
<td>0.515</td>
<td>0.7</td>
</tr>
<tr>
<td>Pump efficiencies</td>
<td>0.6</td>
<td>0.63</td>
<td>0.517</td>
<td>0.3</td>
</tr>
<tr>
<td>Diameter of motionless mixer</td>
<td>0.5</td>
<td>0.475</td>
<td>0.518</td>
<td>0.3</td>
</tr>
<tr>
<td>Electric. cost rate ($/kWh)</td>
<td>$0.05</td>
<td>$0.0475</td>
<td>0.519</td>
<td>0.2</td>
</tr>
<tr>
<td>Fraction of tank used</td>
<td>0.8</td>
<td>0.84</td>
<td>0.521</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: The Cumulative 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 cumulative 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_

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Base value</th>
<th>New Value</th>
<th>Cumulative New NR $/bbl</th>
<th>Add % Change NR/bbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur in feed</td>
<td>2.80%</td>
<td>2.94%</td>
<td>-0.699</td>
<td>+9.3</td>
</tr>
<tr>
<td>Sulfur removed (% of initial)</td>
<td>33.33%</td>
<td>35.00%</td>
<td>-0.626</td>
<td>+10.3</td>
</tr>
<tr>
<td>Bacteria cult. vol. ratio (rv)</td>
<td>0.60</td>
<td>0.57</td>
<td>-0.578</td>
<td>+7.7</td>
</tr>
<tr>
<td>Price of bacteria ($/m3)</td>
<td>$10.00</td>
<td>$9.50</td>
<td>-0.533</td>
<td>+7.8</td>
</tr>
<tr>
<td>Batch processing time (hr)</td>
<td>48</td>
<td>45.6</td>
<td>-0.486</td>
<td>+8.8</td>
</tr>
<tr>
<td>Oil to be treated (gal) (fixed time)</td>
<td>250,000</td>
<td>262,500</td>
<td>-0.445</td>
<td>+8.4</td>
</tr>
<tr>
<td>No. of employees at a time</td>
<td>2.0</td>
<td>1.9</td>
<td>-0.419</td>
<td>+5.8</td>
</tr>
<tr>
<td>Stream days in a year</td>
<td>330</td>
<td>346.5</td>
<td>-0.393</td>
<td>+6.3</td>
</tr>
<tr>
<td>Specific gravity of feed</td>
<td>0.80</td>
<td>0.84</td>
<td>-0.387</td>
<td>+1.4</td>
</tr>
<tr>
<td>Sulfur sale value ($/lt)</td>
<td>$50.00</td>
<td>$52.50</td>
<td>-0.384</td>
<td>+0.9</td>
</tr>
<tr>
<td>Pump efficiencies</td>
<td>0.6</td>
<td>0.63</td>
<td>-0.382</td>
<td>+0.4</td>
</tr>
<tr>
<td>Diameter of motionless mixer</td>
<td>0.5</td>
<td>0.475</td>
<td>-0.381</td>
<td>+0.4</td>
</tr>
<tr>
<td>Electric. cost rate ($/kWh)</td>
<td>$0.05</td>
<td>$0.0475</td>
<td>-0.379</td>
<td>+0.3</td>
</tr>
<tr>
<td>Fraction of tank used</td>
<td>0.8</td>
<td>0.84</td>
<td>-0.378</td>
<td>+0.3</td>
</tr>
</tbody>
</table>
5

References

5.1 Costing and Estimating of Process Equipment, Buildings and Structures for Chemical and Petrochemical Plants (In Chronological Order)

5.1.1 Books

"Upgrading Heavy Crude Oil and Residues to Transportation Fuels. Technology, Economics, and Outlook: Phase IV," SFA Pacific, Inc. Mountain View, CA, 1994, 424 p. (A comprehensive costing methodology for evaluating alternative petrochemical upgrading plants and feedstocks has been developed. The methodology was selectively applied to 17 petrochemical upgrading processes, when these processes are treating 7 different types of oil feeds. The Net Realization (NR) for 34 process-feed combinations was calculated. Capital investment costs for equipment and the plant facility are estimated based on the actual plants studied. Another 5 additional process-feed combinations were economically analyzed in a "summary" fashion without calculating NR. Arabian Heavy was used as basecase feed, i.e. the feed was treated by all 22 processes considered in the study. The remaining 6 feeds were treated only by 2 or 3 processes). SFA Pacific, Inc., 444 Castro Street, Suite 920, Mountain View, CA 94041, Phone (415) 969-8876, Fax (415) 969-1317.

"National Building Cost Manual - A Handbook for the Professional Builders," Craftsman Book Co., Carlsbad, CA, 1994, 240p. (Square foot costs for residential, commercial, industrial, and farm buildings. Quickly work up a reliable budget estimate based on actual materials and design features, area, shape, wall height, number of floors, and support requirements. Includes all the important variables that can make any building unique from a cost standpoint).

prices for every common building material. Man-hours, recommended crew, and labor costs for installation. Estimate Writer is an electronic version of the book on computer disk, with a stand-alone estimating program).

"Construction Estimating Reference Data and DataEst," Craftsman Book Co., Carlsbad, CA, 1994, 432p. (Provides 300 man-hour tables for practically every item of construction. Labor requirements are listed for sitework, concrete work, masonry, steel, carpentry, thermal and moisture protection, doors and windows, finishes, mechanical, and electrical. DataEst is a computer estimating program on a high density disk).


"Basic Engineering for Builders," Craftsman Book Co., Carlsbad, CA, 1994, 400p. (Establishes engineering requirements such as sizing of structural members and quantifying steel, concrete, wood, and masonry using only preliminary plans).

"Builder's Comprehensive Dictionary," Craftsman Book Co., Carlsbad, CA, 1994, 532p. (Almost 10,000 definitions, construction terms, over 1,000 detailed illustrations of tools, techniques, and systems, and a separate section of common legal, real estate, and management terms).


5. References


5. References


G.T. Heery, "Time, Cost & Architecture," (exclusively civil engineering and structural costs, however applicable to chemical and petrochemical industry), McGraw-Hill, New York, 1975


G.L. Wells, "Process Engineering With Economic Objective," (Some costing elements are included), Leonard Hill, New York, 1973


H. Popper, "Modern Cost Engineering Techniques," (A collection of articles on cost estimating from Chemical Engineering published during
5. References


"Cost Engineers Notebook," American Assoc. of Cost Engineers, 308 Monongahela Bldg., Morgantown, WV 26505


5.1.2 Articles


5. References


5. References


C.A. Miller, "Converting Construction Costs from One Country to Another," Chem. Eng., July 2, 1979, 89-93


5. References


F.D. Clark, "Cost Control For Process Plants From the Owners View," Chem. Eng., July 7, 1975, 70-77


5. References


5. References


5. References

5.2 Design of a Pilot Plant for Biochemical Upgrading of Heavy Crude Oil (In Chronological Order)

5.2.1 Books


5.2.2 Articles


H.W. Goodner, "A New Way of Quantifying Risks - Par 2," Chemical Engineering, November, 1993, 140-146


5. References


5. References


5. References


L.F. Engle, "Check List for Processing from Start, to Start-Up," Mining Eng., May 1966
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.

\[ y = A + Bx \]  \hspace{1cm} (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 \(i = 1, 2, \ldots n\). 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:

\[ \varepsilon_i = y_i - A - Bx_i \]  \hspace{1cm} (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:

\[ Z = \sum_{i=1}^{n} [y_i - A - Bx_i]^2 \]  \hspace{1cm} (A-3)

The partial derivatives of \(Z\) with respect to A and B are equated to zero in order to find the coefficients that produce the minimum of \(Z\):

\[ \frac{\partial Z}{\partial B} = \sum_{i=1}^{n} -2x_i[y_i - A - Bx_i] = 0 \]  \hspace{1cm} (A-4)

\[ \frac{\partial Z}{\partial A} = \sum_{i=1}^{n} -2[y_i - A - Bx_i] = 0 \]  \hspace{1cm} (A-5)

Eqns. A-4 and A-5 form a system of 2 equations with 2 unknowns, shown below.
Appendix A

\[(\Sigma x_i)A + (\Sigma x_i^2)B = \Sigma x_i y_i \quad (A-6)\]

\[nA + (\Sigma x_i)B = \Sigma y_i \quad (A-7)\]

The solution of the system above is:

\[B = \frac{(\Sigma x_i)(\Sigma y_i) - n(\Sigma x_i y_i)}{(\Sigma x_i)^2 - n(\Sigma x_i^2)} \quad (A-8)\]

\[A = \frac{(\Sigma x_i)(\Sigma x_i y_i) - (\Sigma x_i^2)(\Sigma y_i)}{(\Sigma x_i)^2 - n(\Sigma x_i^2)} \quad (A-9)\]

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:

<table>
<thead>
<tr>
<th>(i)</th>
<th>(x_i)</th>
<th>(y_i)</th>
<th>(x_i y_i)</th>
<th>(x_i^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>33.17</td>
<td>165.8</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>26.02</td>
<td>195.2</td>
<td>56.25</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>20.29</td>
<td>202.9</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>17.71</td>
<td>221.3</td>
<td>156.25</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>11.63</td>
<td>174.5</td>
<td>225</td>
</tr>
</tbody>
</table>

\(n = 5\) \(\Sigma x_i = 50\) \(\Sigma y_i = 108.82\) \(\Sigma x_i y_i = 959.76\) \(\Sigma x_i^2 = 562.5\)

Therefore, using eqns. A-8 and A-9, it follows:

\[B = \frac{50 \times 108.82 - 5 \times 959.76}{50^2 - 5 \times 562.5} = -2.055 \quad (A-10)\]

and

\[A = \frac{50 \times 959.76 - 562.5 \times 108.82}{50^2 - 5 \times 562.5} = 42.31 \quad (A-11)\]

The above procedure is automatically computed by MS EXCEL through the function \text{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


Premuzic, E. T. and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures, Enhanced Oil Recovery, 57, 71, DOE/BC-89/1 (DE89000755), 1989c.


Premuzic, E. T. and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (01/01/91-03/31/91) (BNL #46055), Apr. 1991.

Premuzic, E. T. and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (04/01/91-06/30/91) (BNL #46403), July 1991.

Premuzic, E. T., and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (07/01/91-09/30/91) (BNL #46872), Nov. 1991.


Premuzic, E. T., and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (01/01/92-03/30/92) (BNL #47555), May 1992.


Premuzic, E. T. and Lin, M. S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (07/01/92-09/30/92) (BNL #48381), October 1992.


Premuzic, E.T. and Lin, M.S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures--Quarterly Report (01/01/93-03/31/93) (BNL #49196), June 1993.

Premuzic, E.T. and Lin, M.S. Effects of selected thermophilic microorganisms on crude oils at elevated temperatures and pressures. Quarterly Report (04/01/93-06/30/93) (BNL #49602), Sep. 1993.


Patents


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.