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May 1984

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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for
U.S. DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
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INTRODUCTION

Cost model of phosphoric acid fuel cell powerplant includes two parts: a method for estimation of fuel cell system capital costs, and an economic analysis which determines the levelized annual cost of operating the system used in the capital cost program.

Cost estimates are prepared for a given powerplant based on the equipment specifications discussed in the previous report of the performance model. Costs were estimated by determining the actual capacities of the equipment and the existing cost data. Current costs of these equipments in the form expected to be used were obtained from the references. Total module cost can be obtained by multiplying the equipment cost by the Direct Cost Factor (DCF), Indirect Cost Factor (ICF), and Contingency Factor (CF).

The levelized annual cost of an investment is defined as the minimum constant net revenue required each year of the life of the project to cover all expenses, the cost of money, and the recovery of the initial investment. This is the capital investment analysis approach commonly used by electric utilities.

The cost model has been coded in Fortran programs with several input options. Mathematical formulation and program description will be discussed in this report. A sample problem will be presented to express the inputs and outputs.
I. SYSTEM DESCRIPTION

As shown in Figure 1, methane which is circulated by compressor (C) is preheated by heat exchanger E-1 prior to mixing it with the super heated steam which receives its heat by passing through heat exchanger E-9. Before entering the reformer, the methane steam mixture is heated via heat exchangers E-2 and E-3. Inside the reformer, methane is catalytically reformed by reaction with excess steam to produce carbon monoxide, carbon dioxide, and the desired product, hydrogen. The effluent from the reformer is cooled by flowing through heat exchanger E-2 before it enters the high temperature shift converter S-1. The function of the high temperature shift converter is to increase the hydrogen concentration and to reduce the carbon monoxide concentration of the reformer gas effluent. The temperature of the effluent from the shift converter S-1 is then reduced by passing through heat exchangers E-1, E-9 and E-6 before entering the low temperature shift converter S-2. The low temperature shift converter further increases the hydrogen concentration by promoting the shift reaction at a lower operating temperature. The effluent from the low temperature shift converter then enters the fuel cell containing \( H_2, CO, CH_4, CO_2 \) and \( H_2O \). The fuel cell converts inputs of hydrogen and oxygen to DC power, water and heat. Oxygen is delivered to the fuel cell by air compressor A, which also provides air to the reformer burner. The spent fuel from the fuel cell anode goes to the burner after mixing with air supplied by compressor A.

Before entering the burner, the mixture is preheated by the burner effluent via heat exchanger E-4. The spent fuel is then burned with whatever additional methane is needed to provide the thermal energy necessary for the reformer reaction.

2
Figure 1. Flow diagram of CSU designed PAC system.
Heat generated in the fuel cell is removed by heat exchangers E-7 and E-10. Heat from heat exchanger E-7 can then be utilized in industrial heat processing or space heating and cooling, while exchanger E-10 is used to preheat the water supplied by liquid separator Q to provide the necessary steam needed for the reforming process. The effluents from the burner and fuel cell cathode will have their water removed and separated by condenser E-5 and liquid separator Q before allowing them to be exhausted to the atmosphere.
II. COST MATHEMATICAL MODEL

2.1 Capital Investment

Total module cost of a piece of equipment can be separated into two parts: FOB equipment cost and the working capital costs; the latter is related to the former. The relationship of total module cost and FOB equipment cost is shown in Figure 2, where the total module cost is obtained by multiplying the purchased equipment cost (FOB) by three factors: Direct Cost Factor (DCF), Indirect Cost Factor (ICF), and Contingency Factor (CF). The definitions of these are also shown in the figure. DCF and ICF of each equipment can be obtained from Refs. 3 and 4, where CF is the input option. The working capital cost is the difference of these two kinds of cost.

All the costs were corrected by the Marshall and Swift cost index to be in constant mid-1981 dollars which is basic year used in the model.

Equipment Cost

There are several methods for estimating equipment cost. Three of them were used in the developed model for different components, which are power factor method, interpolation of true cost data, and unit-cost estimate. The fuel cell stack cost was estimated by unit-cost estimate method. For pumps and power inverter, linear interpolation was used to estimate the cost from tabulated data published by Exxon (Ref. 1). The power factor method was most used for the estimation of equipment cost in this model, which includes the reformer, the shift converters, the heat exchangers, the separator, and the compressors.
Figure 2

GENERALIZED INVESTMENT COST ESTIMATING LOGIC (REF. 3)

- FOB Equipment
- Material Factor
- Labor Factor

Direct M&L Cost
- Engineering
- Construction Overhead

Bare Module Cost
- Contingency, etc.
- Fee

Total Module Cost

\[
\text{Total Module Cost} = 100 \times \text{DCF} \times \text{ICF} \times \text{CF}
\]

\[
\begin{align*}
\text{FOB Equipment} & \rightarrow 100 \\
\text{Material Factor} & \rightarrow xxx \\
\text{Labor Factor} & \rightarrow xx \\
\text{Direct M&L Cost} & \rightarrow xxx \\
\text{Engineering} & \rightarrow xx \\
\text{Construction Overhead} & \rightarrow xx \\
\text{Bare Module Cost} & \rightarrow xxx \\
\text{Contingency, etc.} & \rightarrow xx \\
\text{Fee} & \rightarrow x
\end{align*}
\]

\[
\begin{align*}
\text{x.xx Direct Cost Factor (DCF)} & \text{[Piping, Concrete, Steel, Instruments, Electrical, Insulation, Paint, & Labor]} \\
\text{x.xx Indirect Cost Factor (ICF)} & \\
\text{x.xx Contingency Factor (CF)} & = 100 \times \text{DCF} \times \text{ICF} \times \text{CF}
\end{align*}
\]
Briefly, the power factor method is

\[ \frac{C}{S} = a_1 S^{a_2} + a_3 \]  

where \( C \) = cost
\( S \) = capacity

\( a_1, a_2, \) and \( a_3 \) are coefficients to be determined

From (1) \( \ln \left( \frac{C}{S} - a_3 \right) = \ln a_1 + a_2 \ln S \)  

A linear regression on sample cost data will provide the values of \( a_1, a_2, \) and \( a_3 \). Cost data have been obtained from the sources listed in the references.

The linear interpolation algorithm is

\[ Y = YT(I-1) + \left[ YT(I) - YT(I-1) \right] \left[ X - XT(I-1) \right] / \left[ XT(I) - XT(I-1) \right] \]  

where \( Y \) is the cost of \( X \) capacity
\( YT(I) \) is the listing cost of \( XT(I) \) listing capacity.

The stack cost estimates were based on calculations of actual quantities of raw materials used to fabricate the components (unit-cost estimate). Current cost of raw materials, in the form expected to be used, were obtained from Chemical Marketing Report (Ref. 10) and Refs. 1 and 2. Fabrication costs were then determined by multiplying the material cost by a manufacturing cost factor, which was selected based on the production rate and the degree of automation envisioned for the manufacturing facility. The factor reflects manufacturing value added, including direct and supervisory labor plus other manufacturing burdens (e.g., maintenance and inventory costs). For example, the cost of catalyst (platinum) is

\[ CCP = (CPL \times LCP \times AAXCELL \times NS) \times (1 + MCP) \]
Energy Related (E): purchased power and fuel

Non-Energy Related (NE): other variables and semi-variables

Fixed Charges: depreciation, return-on-investment; income taxes, and local taxes and insurance.

 Those cost elements were first converted into a series of future cash flows (escalation allowed) which were then levelized to obtain a uniform annual cost series. This procedure is presented graphically in Figure 3.

Levelized annual costs were determined from the following generalized relationship:

\[
LAC = I x FCR_E \left[ \sum_{n=1}^{N} \frac{(1+i + e_E)^n}{(1+y)^n} \right] CRF_Y + NE \left[ \sum_{n=1}^{N} \frac{(1+i + e_{NE})^n}{(1+y)^n} \right] CRF_Y
\]

where \( FCR = \) fixed charge rate, and equal to

\[
\frac{CRF_m, n_B}{(1-t)} [1-t (DEP)-C]
\]

and \( CRF_m, n_B: \) capital recovery factor for the after-tax cost of capital \( m \) and the economic life \( n_B \)

\( t: \) tax rate

\( C: \) investment tax credit rate

\( DEP: \) levelized depreciation factor (Sum of Years Digit) and

\[
z \left[ n_T - 1/CRF_m, n_T \right]
\]

equal to \( \frac{n_T (n_T + 1)^m}{n_T (n_T + 1)^m} \)

\( n_T: \) tax depreciation life

\( m: \) after tax cost of capital at the assumed inflation rate
I : total module cost in mid-1981 dollars, and equal to $K_m K_e K (1 + e_k + i_o)^{N^*-N_o-L} + W$

and $K_m : \text{cost-of-capital factor} = e^{0.418mL}$

$L : \text{design and construction time}$

$K_e : \text{escalation factor} = e^{0.562(e_k + i_o)L}$

$K : \text{equipment cost}$

$W : \text{working capital}$

$e_k : \text{real capital cost escalation per year}$

$N^*: \text{first year of commercial operation of the investment}$

$N_o: \text{the year used as basis for the cost estimate}$

$i_o : \text{annual inflation rate}$

$E : \text{annual energy cost}$

$NE : \text{annual non-energy cost}$

$eE : \text{annual energy escalation}$

$eNE : \text{annual non-energy escalation}$

$\gamma : \text{weighted cost of capital with inflation } i_o$

$n : \text{project life}$

$CRF_r: \text{capital recovery factor at } \gamma \text{ cost of capital and } n \text{ years, which equal to}$

$$\frac{(1+\gamma)^n - 1}{\gamma(1+\gamma)^n}$$ (8)
where CPL : cost of platinum, $/g
LCP : loading of platinum, g/cm²
AA : active area per cell, cm²
NCCELL : number of cells per stack
NS : number of stacks
MCP : manufacturing factor for catalyst.

The manufacturing cost factors used for estimating the cost of PAFC stack in this model were adopted from Ref. 1. More detailed description of this factor can be found in Ref. 4, pages 191-201.

2.2 Levelized Annual Cost Analysis

The levelized annual cost (LAC) of an investment is defined as the minimum constant net revenue required each year of the life of the project to cover all expenses, the cost of money, and the recovery of the initial investment. LAC is a comparative measure of both the fixed and variable costs associated with the investment, incurred at different times throughout the life of the project.


The computation of the levelized annual cost was accomplished by segregating annual costs into three categories, namely, energy related costs, non-energy related costs and fixed charges. The cost items grouped in each category were as follows:
**Figure 3**

**APPROACH TO LEVELIZED ANNUAL COST ANALYSIS**

**PROJECT LIFE**

0 1 5 10 15 20

\{NE\}

\{E\}

\(K = \text{Conversion Factor}

\text{Defined as}

\[ \sum_{n=1}^{20} \frac{(1+i+e)^n}{(1+r)^n} \]

where:

- \(i\) = inflation
- \(e\) = real escalation
- \(n\) = year
- \(r\) = weighted cost of capital

**LEVELIZED ANNUAL COSTS**

\(K_{\text{NE}}(\text{NE}) \text{ CRF}\)

\(K_{\text{E}}(\text{E}) \text{ CRF}\)

\(\text{(I). FCR}\)

**I** = Capital Investment

**NE** = Non-energy Cost

**E** = Energy Cost

**FCR** = Fixed Charge Rate with SYD depreciation and 10% tax credit
III. COST COMPUTER MODEL

3.1 Program

There is one subroutine (RLIN) in addition to the BLOCK DATA and MAIN programs in the cost computer model. The MAIN program estimates the capital investment of the PAFC powerplant, and calculates the levelized annual cost using the algorithm described in the previous chapter. The subroutine RLIN do the linear interpolation with two sets of input serial data and a specific capacity. The BLOCK DATA supplies the cost data tables, for the pump and the power inverter, from Ref. 1, and also the physical properties of the gases in the system. Table 1 shows the nomenclature of the variables.

3.2 Program Operation

The program input consists of a set of NAMELIST data which must be in a specified order. The first NAMELIST set is called INDEX and contains the Marshall and Swift cost index of the specified time. All the indices are obtained from Chemical Engineering magazine.

The second set (CONST) has the constants used in the power factor method (Section 2.1). The general form used here is

\[ C = a_1 \left(\frac{S}{a_2}\right)^{a_3} \]  

(9)

where \( C \) is cost and \( S \) is capacity. The definitions of the constants for the equipment in this NAMELIST are listed in Table 2.

The third set (FUCEC) contains the amount, the unit cost, and the manufacturing cost factor of the material used in manufacturing the PAFC stack.
### TABLE 1

**NOMENCLATURE OF COST COMPUTER MODEL**

<table>
<thead>
<tr>
<th>Equipment Number and Unit for Estimating the Cost</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fuel cell stack</td>
<td>kW</td>
</tr>
<tr>
<td>2 reformer</td>
<td>MBtu/hr ejected</td>
</tr>
<tr>
<td>3 fuel compressor</td>
<td>brake HP</td>
</tr>
<tr>
<td>4 heat exchanger</td>
<td>transfer area ft²</td>
</tr>
<tr>
<td>5 separator</td>
<td>g-mole water</td>
</tr>
<tr>
<td>6 pump</td>
<td>W</td>
</tr>
<tr>
<td>7 condenser</td>
<td>gal/min water</td>
</tr>
<tr>
<td>8 high temperature shift converter</td>
<td>g-mole H₂</td>
</tr>
<tr>
<td>9 low temperature shift converter</td>
<td>g-mole H₂</td>
</tr>
<tr>
<td>10 power inverter</td>
<td>V</td>
</tr>
<tr>
<td>11 air compressor</td>
<td>ft³/min</td>
</tr>
</tbody>
</table>

### Cost of Fuel Cell Stack

| AA: active area per cell, cm²                          | |
| NS: number of stacks                                  | |
| SV: operating voltage, V                              | |
| CPL: cost of platinum, $/g                            | |
| CMRIN: Chemical Marketing Reporter index of raw material | |
| NCELL: number of cells per stack                      | |
| LCP: platinum loading, g/cm²                          | |
| LESL: electrolyte support layers loading, g/cm²       | |
| LEM: electrolyte matrix loading, g/cm²                | |
| LBP: bipolar plate loading, g/cm²                    | |
| CKW: capacity of fuel cell stack, kW                  | |
| MCP: mfg. cost factor of catalyst                     | |
| MESL: mfg. cost factor of electrolyte support layers  | |
| MEM: mfg. cost factor of electrolyte matrix           | |
| MBP: mfg. cost factor of bipolar plate                | |
| MCC: mfg. cost factor of cooling cartridge            | |
| MSH: mfg. cost factor of stack hardware               | |
| CCP: cost of platinum (catalyst)                      | |
| CGFP: cost of electrolyte support layers - graphite fiber paper | |
| CEM: cost of electrolyte matrix - silicon carbide fiber | |
| CBP: cost of bipolar plate - carbon/phenolic resin    | |
| CCC: cost of cooling cartridge - carbon plate with copper tube grid | |
| CSH: cost of stock hardware - end plates, manifolding, tie rods | |
| CGF: unit cost of graphite fiber paper, $/g           | |
| CSC: unit cost of silicon carbide fiber, $/g          | |
| CCPR: unit cost of carbon/phenolic resin, $/g         | |
| CMRO: CMR index of data year                          | |

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TABLE 1 (cont’d)

NOMENCLATURE OF COST COMPUTER MODEL

Cost of Other Equipments

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1</td>
<td>power conditioner voltage, V</td>
</tr>
<tr>
<td>CC2</td>
<td>power conditioner cost, $/kW</td>
</tr>
<tr>
<td>CP1</td>
<td>pump power, W</td>
</tr>
<tr>
<td>CP2</td>
<td>pump cost, $</td>
</tr>
<tr>
<td>HCH4</td>
<td>high heating value of methane, Cal/g-mole</td>
</tr>
<tr>
<td>HCO</td>
<td>high heating value of carbon monoxide, Cal/g-mole</td>
</tr>
<tr>
<td>HH2</td>
<td>high heating value of hydrogen, Cal/g-mole</td>
</tr>
<tr>
<td>COST(I)</td>
<td>cost of equipment I, $</td>
</tr>
<tr>
<td>CEQ(I,J)</td>
<td>capacity of equipment I number J</td>
</tr>
<tr>
<td>IN81</td>
<td>Marshall and Swift index of mid-1981</td>
</tr>
<tr>
<td>IN80</td>
<td>Marshall and Swift index of 1980</td>
</tr>
<tr>
<td>IN79</td>
<td>Marshall and Swift index of 1979</td>
</tr>
<tr>
<td>IN791</td>
<td>Marshall and Swift index of January 1979</td>
</tr>
<tr>
<td>IN77</td>
<td>Marshall and Swift index of 1977</td>
</tr>
<tr>
<td>IN75</td>
<td>Marshall and Swift index of 1975</td>
</tr>
<tr>
<td>IN68</td>
<td>Marshall and Swift index of 1968</td>
</tr>
<tr>
<td>IN67M</td>
<td>Marshall and Swift index of mid-1967</td>
</tr>
<tr>
<td>CH4</td>
<td>methane input, g-mole/hr</td>
</tr>
<tr>
<td>CO</td>
<td>carbon monoxide input, g-mole/hr</td>
</tr>
<tr>
<td>H2</td>
<td>hydrogen input, g-mole/hr</td>
</tr>
<tr>
<td>COMP</td>
<td>brake hp of compressor, hp</td>
</tr>
<tr>
<td>HE(J)</td>
<td>transfer area of heat exchanger number J, m²</td>
</tr>
<tr>
<td>SEPR</td>
<td>amount of steam input in separator, g-mole/hr</td>
</tr>
<tr>
<td>PUM</td>
<td>power of pump, hp</td>
</tr>
<tr>
<td>COND</td>
<td>inlet H₂O flow rate of condenser</td>
</tr>
<tr>
<td>HSHIF</td>
<td>inlet hydrogen flow rate of high temp. shift converter, g-mole/hr</td>
</tr>
<tr>
<td>LSHIF</td>
<td>inlet hydrogen flow rate of low temp. shift converter, g-mole/hr</td>
</tr>
<tr>
<td>AIRC</td>
<td>inlet air flow rate, g-mole/hr</td>
</tr>
</tbody>
</table>

Total Module Cost and Operation Cost

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCF(I)</td>
<td>direct cost factor of equipment I</td>
</tr>
<tr>
<td>ICF(I)</td>
<td>indirect cost factor equipment I</td>
</tr>
<tr>
<td>CF</td>
<td>contingency factor of equipment</td>
</tr>
<tr>
<td>CMAIN</td>
<td>maintenance cost of fuel cell system, $/kWh DC</td>
</tr>
<tr>
<td>CREPL</td>
<td>factor of capital cost for replacement</td>
</tr>
<tr>
<td>MTIME</td>
<td>times which replacement will occur for 20 years usage</td>
</tr>
<tr>
<td>WATER</td>
<td>cooling water input, g-mole/hr</td>
</tr>
<tr>
<td>CWAT</td>
<td>cost of cooling water, $/m³</td>
</tr>
<tr>
<td>AVER</td>
<td>mean factor of cooling water for recycle</td>
</tr>
<tr>
<td>ENPU</td>
<td>input fuel flow rate, g-mole/hr</td>
</tr>
<tr>
<td>AVHT</td>
<td>average heating value of input fuel, Btu/ft³</td>
</tr>
<tr>
<td>CENG</td>
<td>cost of energy fuel, $/GJ</td>
</tr>
</tbody>
</table>
**TABLE 1 (cont’d)**

**NOMENCLATURE OF COST COMPUTER MODEL**

**Levelized Annual Analysis**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>cost of common equity</td>
</tr>
<tr>
<td>CD</td>
<td>cost of debt</td>
</tr>
<tr>
<td>CP</td>
<td>cost of preferred equity</td>
</tr>
<tr>
<td>EK</td>
<td>real capital cost escalation per year; i.e., rate of capital cost escalation</td>
</tr>
<tr>
<td>ESC</td>
<td>escalation, decimal</td>
</tr>
<tr>
<td>FC</td>
<td>ratio of common equity</td>
</tr>
<tr>
<td>FD</td>
<td>ratio of debt capital to total capital</td>
</tr>
<tr>
<td>FL</td>
<td>annual inflation rate</td>
</tr>
<tr>
<td>FP</td>
<td>ratio of preferred equity</td>
</tr>
<tr>
<td>L</td>
<td>design and construction time, year</td>
</tr>
<tr>
<td>NE</td>
<td>economic life</td>
</tr>
<tr>
<td>NSTAR</td>
<td>first full year of commercial operation of investment change above or below the rate of inflation</td>
</tr>
<tr>
<td>NT</td>
<td>tax depreciation life</td>
</tr>
<tr>
<td>NZERO</td>
<td>the year used as basic year</td>
</tr>
<tr>
<td>TAX</td>
<td>tax rate</td>
</tr>
<tr>
<td>TAXL</td>
<td>state and local tax</td>
</tr>
<tr>
<td>TC</td>
<td>investment tax credit rate</td>
</tr>
<tr>
<td>CAKE</td>
<td>escalation factor</td>
</tr>
<tr>
<td>CAKM</td>
<td>cost-of-capital factor</td>
</tr>
<tr>
<td>CAPIT</td>
<td>capital investment</td>
</tr>
<tr>
<td>CEN</td>
<td>levelized energy cost</td>
</tr>
<tr>
<td>CN</td>
<td>non-energy cost</td>
</tr>
<tr>
<td>CRFRE</td>
<td>capital recovery factor at R for economic life</td>
</tr>
<tr>
<td>CRFRK</td>
<td>capital recovery factor at AK for energy in economic life</td>
</tr>
<tr>
<td>CRFRT</td>
<td>capital recovery factor at R for tax depreciation life</td>
</tr>
<tr>
<td>DEP</td>
<td>levelized depreciation factor for sum of years digits (SYD)</td>
</tr>
<tr>
<td>FCL</td>
<td>levelized fixed charges</td>
</tr>
<tr>
<td>FCR</td>
<td>fixed charge rate</td>
</tr>
<tr>
<td>R</td>
<td>after tax cost of capital</td>
</tr>
<tr>
<td>RLAC</td>
<td>levelized annual cost</td>
</tr>
<tr>
<td>TLIN</td>
<td>levelized local tax and insurance</td>
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</table>
The fourth set (INPUTS) consists of the input flow composition of fuel compressor, condenser, separator, high temperature and low temperature shift converters, the transfer area of each heat exchanger, and power needed in compressor and pump.

The fifth set (FACTR) contains direct cost factor, indirect cost factor, and contingency factor of each equipment.

The sixth and seventh sets (NENEG and ENG) include the amount and unit cost of fuel and utilities used in the system. The maintenance information is in NENEG.

The last NAMELIST set (ECON) contains all the necessary data used for LAC analysis.

All of the input variables are listed in Table 3, along with their units and numerical values in the sample run.

3.3 Sample Problem

The computer code described in the previous sections was used to estimate the equipment capital cost and the levelized annual cost of CSU designed PAFC powerplant (Figure 1). A 100 kW powerplant was considered here, which included one fuel cell stack containing 200 cell plates with 1900 cm$^2$ active area in each cell plate. The middle of year 1981 was chosen as the basic year for constant dollar estimation.
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Constants Used in Equation 9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a_1 )</td>
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<tr>
<td>Reformer</td>
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<td>C18</td>
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<td>NAMELIST Name</td>
<td>Variable Name</td>
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<tr>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>INDEX</td>
<td>IN81</td>
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<tr>
<td>INDEX</td>
<td>IN80</td>
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<tr>
<td>INDEX</td>
<td>IN791</td>
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<td>INDEX</td>
<td>IN75</td>
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<tr>
<td>INDEX</td>
<td>IN68</td>
</tr>
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<td>IN67M</td>
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<td>C1...C19</td>
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<td>Variable</td>
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<td>----------</td>
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<td>CO</td>
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<tr>
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<td>H2</td>
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<td>COMP</td>
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<td>Variable Name</td>
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<td>NSTAR</td>
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<tr>
<td>ECON</td>
<td>ZERO</td>
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</table>
Figure 4

SAMPLE INPUT DATA

&INDEX IN81=696.9,IN80=659.6,IN791=561.,IN77=505.4,IN75=444.3,IN68=273.,
,IN67M=270.,
&END
&CONST C1=7620.,C2=.85,C3=514.55,C4=.82,C5=162.106,C6=.6934,
C7=1500.,C8=81720.,C9=.64,C10=104.4,C11=.5,C12=900.
C13=4310.,C14=.69,C15=1320.,C16=454.,C17=.69,C18=7.,C19=.68,
&END
&FUCEC AA=1900.,NS=4,5V=133.,CPL=16.75,CMRIN=158.34,NCELL=200,LCP=.00075
,LES=0.024,LEM=0.039,LBP=0.44,CKW=100.,MCP=0.05,MESL=0.6,MEM=0.6,MBP=1.5
,MCC=1.5,MSH=1.4,CGF=0.066,CSC=0.0176,CCPR=0.0009,CMROT=198.66,
&END
&INPUTS CH4 = 172.6,CO = 2.79,H2=867.63,COMP = 1.62,
HE=0.3945,1.4024,1.5395,2.3735,1.4953,0.2,0.6418,SEPR=6820.63,PUM=0.00226,
COND=132960.37,51396.,HSHIF=3708.6,LSHIF=3925.62,AIRC=24524.,
&END
&FACTR DCF = 1.15,1.42,1.15,1.35,1.14,1.75,1.16,1.15,1.15,1.15,1.75,
ICF=1.14,1.28,1.14,1.407,1.15,1.45,1.5086,1.14,1.14,1.14,1.45,CF=0.2,
&END
&HNEG CMAIN=0.00065,CREPL=0.5,MTIME=4,WATER=184356.,CWAT=0.0013157,AVER=12.,
&END
&ENG ENPU=1405.16,AVHT=360242.64,CENG=6.29,
&END
&ECON TAX=0.48,TC=0.1,ESC=0.024,CD=0.03,CP=0.09,CC=0.09,FD=0.4,FP=0.,FC=0.6
,TAXL=0.02,FL=0.,NT=20,NE=20,L=1,Ek=0.,NSTAR=1932,NZERO=1981,
&END
Figure 5
SAMPLE COMPUTER RUN

&INDEX
IN81 = 696.8999
IN80 = 659.5999
IN791 = 561.0
IN77 = 505.3999
IN75 = 444.2998
IN68 = 273.0
IN67M = 270.0
&END
&CONST
C1 = 7620.0
C2 = 0.850
C3 = 514.5498
C4 = 0.820
C5 = 162.1060
C6 = 0.69340
C7 = 1500.0
C8 = 817200.0
C9 = 0.640
C10 = 104.40
C11 = 0.50
C12 = 900.0
C13 = 4310.0
C14 = 0.690
C15 = 1320.0
C16 = 4540.0
C17 = 0.690
C18 = 7.0
C19 = 0.6799999
&END
&FUUCEC
AA = 1900.0
NS = 4
SV = 133.0
CPL = 16.750
CMRIN = 158.340
NCELL = 200
LCP = 0.7499999E-03
LESL = 0.240E-01
LEM = 0.390E-01
LBP = 0.440
CKW = 100.0
MCP = 0.50E-01
MESL = 0.60
MEM = 0.60
MBP = 1.50
MCC = 1.50
MSH = 1.40
CGF = 0.6599998E-01
CSC = 0.1760E-01
CCPR = 0.8999999E-03
CMRO = 198.660
&END
&INPUTS
CH4 = 172.60
C0 = 2.790
H2 = 867.6299
COMP = 1.620
HE = 0.39450, 1.402399, 1.539499, 2.37350, 1.495299, 0.20, 0.64180
SAMPLE COMPUTER RUN

SEPR = 6820.629
PUM = 0.2260E-02
COND = 132960.3, 51396.0
HSHIF = 3708.60
LSHIF = 3925.620
AIRC = 24524.0
&END
&FACTR
ICF = 1.139999, 1.280, 1.139999, 1.4070, 1.150, 1.450, 1.508599, 3X1.139999
1.450
DCF = 1.150, 1.419999, 1.150, 1.349999, 1.139999, 1.750, 1.160, 3X1.150, 1.750
CF = 0.20
&END
&NENEG
CMAIN = 0.6499998E-03
CREPL = 0.50
MTIME = 4
WATER = 184356.0
CUTER = 0.131570E-02
AVER = 12.0
&END
&ENG
ENPU = 1405.160
AUHT = 360242.6
CENG = 6.290
&END

COST ANALYSIS FOR 100KW FUEL CELL SYSTEM

MID-1981 MONEY
100% LOAD FACTOR

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>CAPITAL COST (F.O.B)</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST(1)</td>
<td>0.28001E 05</td>
<td>44.80</td>
</tr>
<tr>
<td>COST(2)</td>
<td>0.85823E 04</td>
<td>13.73</td>
</tr>
<tr>
<td>COST(3)</td>
<td>0.19509E 04</td>
<td>3.12</td>
</tr>
<tr>
<td>COST(4)</td>
<td>0.76818E 04</td>
<td>12.29</td>
</tr>
<tr>
<td>COST(5)</td>
<td>0.96691E 02</td>
<td>0.15</td>
</tr>
<tr>
<td>COST(6)</td>
<td>0.52845E 03</td>
<td>0.85</td>
</tr>
<tr>
<td>COST(7)</td>
<td>0.14186E 04</td>
<td>2.27</td>
</tr>
<tr>
<td>COST(8)</td>
<td>0.11188E 04</td>
<td>1.79</td>
</tr>
<tr>
<td>COST(9)</td>
<td>0.16464E 04</td>
<td>2.63</td>
</tr>
<tr>
<td>COST(10)</td>
<td>0.10533E 05</td>
<td>16.85</td>
</tr>
<tr>
<td>COST(11)</td>
<td>0.93940E 03</td>
<td>1.50</td>
</tr>
</tbody>
</table>

TOTAL CAPITAL COST (F.O.B) 0.62497E 05
TOTAL WORKING CAPITAL COST 0.36873E 05
ANNUAL O&M 0.83828E 04
ANNUAL ENERGY COST IN YEAR J = 0 0.61490E 05

&CON
TAX = 0.480
TC = 0.9999996E-01
ESC = 0.240E-01
CD = 0.30E-01
CP = 0.8999997E-01
CC = 0.8999997E-01
FD = 0.40
### SAMPLE COMPUTER RUN

<table>
<thead>
<tr>
<th>FP</th>
<th>0.0</th>
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<tbody>
<tr>
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<td>0.0</td>
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<tr>
<td>NT</td>
<td>20</td>
</tr>
<tr>
<td>NE</td>
<td>20</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
</tr>
<tr>
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<td>0.0</td>
</tr>
<tr>
<td>NSTAR</td>
<td>1982</td>
</tr>
<tr>
<td>NZERO</td>
<td>1981</td>
</tr>
</tbody>
</table>

#### INFORMATION OF ECONOMIC FACTOR:

- **LEVELIZED DEPRECIATION FACTOR (SYD)**: 0.67699
- **FIXED CHARGE RATE**: 0.09791
- **CAPITAL RECOVERY FACTOR OF ECONOMIC LIFE**: 0.08718
- **CAPITAL RECOVERY FACTOR OF TAX DEPRECIATION LIFE**: 0.08718

- **LEVELIZED FIXED CHARGES**: 0.98846E 04
- **LEVELIZED ENERGY COST**: 0.76084E 05
- **TOTAL LEVELIZED COST**: 0.97380E 05
The following are the summary of the results:

1. Equipment Capital Cost (FOB) - in mid-1981 money

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost (FOB)-$</th>
<th>Percentage of Total FOB</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel cell module</td>
<td>28001</td>
<td>44.8</td>
</tr>
<tr>
<td>reformer</td>
<td>8582</td>
<td>13.7</td>
</tr>
<tr>
<td>fuel compressor</td>
<td>1951</td>
<td>3.1</td>
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<tr>
<td>heat exchangers</td>
<td>7682</td>
<td>12.3</td>
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<tr>
<td>separator</td>
<td>97</td>
<td>0.2</td>
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<tr>
<td>pump</td>
<td>528</td>
<td>0.9</td>
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<tr>
<td>condenser</td>
<td>1419</td>
<td>2.3</td>
</tr>
<tr>
<td>high temperature shift converter</td>
<td>1119</td>
<td>1.8</td>
</tr>
<tr>
<td>low temperature shift converter</td>
<td>1646</td>
<td>2.6</td>
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<tr>
<td>power inverter</td>
<td>10535</td>
<td>16.8</td>
</tr>
<tr>
<td>air compressor</td>
<td>939</td>
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</tr>
</tbody>
</table>

**total** 62497 100.0

2. Total Working Cost

\[
\text{Total Working Cost} = \text{total module cost} - \text{total FOB cost (Figure 2)}
\]

36873 = 99370 - 62497

3. Levelized Annual Analysis

<table>
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</tr>
<tr>
<td>levelized local tax and insurance</td>
</tr>
<tr>
<td>levelized energy cost</td>
</tr>
<tr>
<td>levelized fixed charges</td>
</tr>
</tbody>
</table>

**total levelized annual cost** 97380

The required CPU time to run this sample problem is less than 0.01 minute on IBM/370.
REFERENCES


8. NASA LeRC Cost Data of Fuel Cell Power Section and Fuel Processing section, in Ref. 2.


LISTING OF THE COST COMPUTER MODEL
THIS PROGRAM IS TO CALCULATE GENERALIZED INVESTMENT COST ESTIMATING LOGIC

WHICH IS RECOMMENDED BY K. M. GUTHRIE, "PROCESS PLANT ESTIMATING, EVALUATION..."

AND CONTROL

C THIS PROGRAM IS TO CALCULATE GENERALIZED INVESTMENT COST ESTIMATING LOGIC

C WHICH IS RECOMMENDED BY K. M. GUTHRIE, "PROCESS PLANT ESTIMATING, EVALUATION..."

C AND CONTROL

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** DEFINITION: **

** COST(I): COST OF EQUIPMENT I **

** CEQ(I,J) = CAPACITY OF EQUIPMENT I NO.J (ACCORDING TO THE COST ESTIMATE) **

** INPUT FUNCTIONS FOR CALCULATING COST OF EACH EQUIPMENT **

** BASIS: MID-1981 MONEY **

** 100% LOAD FACTOR **

** F2(S)=C1*(S)*C2*IN81/IN68 **

** F3(S)=C3*(S)*C4*IN81/IN68 **

** F4(S)=C5*IN81/IN79 **

** F5(S)=C7*(S/C8)*C9*IN81/IN77 **

** F7(S)=C10*(S)*C11*IN81/IN67M **

** F8(S)=C12*(S/C13)*C14*IN81/IN77 **

** F9(S)=C15*(S/C16)*C17*IN81/IN77 **

** F11(S)=C18*(S)*C19*IN81/IN68 **

** READ IN THE MARSHALL AND SWIFT INDEX **

** IN81: INDEX OF MID-1981 **

** IN80: INDEX OF 1980 **

** IN79: INDEX OF 1979 **

** IN791: INDEX OF 1979 JAN. **

** IN77: INDEX OF 1977 **

** IN75: INDEX OF 1975 **

** IN68: INDEX OF 1968 **

** IN67M: INDEX OF MID-1967 **

** READ(5,INDEX) **

** WRITE(6,INDEX) **

** READ(5,CONST) **

** WRITE(6,CONST) **

** CAL. THE COST OF FUEL CELL **

** INPUT: **

** AA: ACTIVE AREA PER CELL (CM^2) **

** NS: NUMBER OF STACKS **

** SV: STACK VOLTAGE (VOLT) **

** CPL: COST OF PLATINUM (S/G) -- BASED ON BASIC YEAR **

** CMRIN: CMR (CHEMICAL MARKETING REPORTER) INDEX OF RAW MATERIAL OF BASI **

** NCELL: NUMBER OF CELLS PER STACK **

** LCP: LOADING OF PLATINUM (G/CM^2) **

** LESL: LOADING OF ELECTROLYTE SUPPORT LAYERS (G/CM^2) **

** LEM: LOADING OF ELECTROLYTE MATRIX (G/CM^2) **
CO20011200  C LBP:  LOADING OF BIPOLAR PLATE (G/CMX2)
CO20011300  C CKW:  CAPACITY OF THE FUEL CELL (KW)
CO20011400  C MCP:  MFG. COST FACTOR OF CATALYST
CO20011500  C MEL:  MFG. COST FACTOR OF ELECTROLYTE SUPPORT LAYERS
CO20011600  C MEM:  MFG. COST FACTOR OF ELECTROLYTE MATRIX
CO20011700  C MBP:  MFG. COST FACTOR OF BIPOLAR PLATE
CO20011800  C MCC:  MFG. COST FACTOR OF COOLING CARTRIDGE
CO20011900  C MSH:  MFG. COST FACTOR OF STACK HARDWARE
CO20012000  C CCP:  COST OF CATALYST -- PLATINUM
CO20012100  C CGFP:  COST OF ELECTRODE SUPPORT LAYERS -- GRAPHITE FIBER PAPER
CO20012200  C CEM:  COST OF ELECTROLYTE MATRIX -- SILICON CARBIDE FIBER
CO20012300  C CBP:  COST OF BIPOLAR PLATE -- CARBON/PHENOLIC RESIN
CO20012400  C CCC:  COST OF COOLING CARTRIDGE -- CARBON PLATE WITH COPPER TUBE GRID
CO20012500  C CSH:  COST OF STACK HARDWARE -- END PLATES, MANIFOLDING, TIE RODS
CO20012600  C CGF:  UNIT COST OF GRAPHITE FIBER PAPER, $/G
CO20012700  C CSC:  UNIT COST OF SILICON CARBIDE FIBER, $/G
CO20012800  C CCPR:  UNIT COST OF CARBON/PHENOLIC RESIN, $/G
CO20012900  C CMROT:  CMR INDEX OF DATA YEAR

READ (5, FUCEC)
WRITE (6, FUCEC)
CCP = (CPLXLCXP*AA*HCELL*NS)*(1.+MCP)
CGFP = (CGFXLESL*AA*HCELL*NS*CMRIN/CMROT)*((1.+MESL)
CEM = (CSCXLEM*AA*HCELL*NS*CMRIN/CMROT)*(1.+MEM)
CBP = (CCPRXLB*AA*HCELL*NS*CMRIN/CMROT)*(1.+MBP)
CCS = CCP/(1.+MBP)*1.+MCC)
CASS = CBP/(1.+MBP)*1.+MCC
CCC = CBP/(1.+MBP)*1.+MCC
COST(1) = CCP + CGFP + CEM + CBP + CCC + CSH
COST(2) = F2(CEQ(2,D)
CEQ(3,1) = COMP
COST(3) = F3(CEQ(3,D
COST(4) = 0.
DO 1 K = 1, 7

READ (5, INPUTS)
WRITE (6, INPUTS)
CEQ(2,1) = (CH4*HCH4 + CO*HCO + H2*HH2)*3.97E-3/1. E+6
COST(2) = F2(CEQ(2,1))
CEQ(3,1) = COMP
COST(3) = F3(CEQ(3,1))
COST(4) = 0.
DO 1 K = 1, 7
CEQ(4,K) = HE(K) / 3.048 * 10^2
CEQ(5,1) = SEPR
CEQ(5,1) = PUM * 745.7
CALL RLIN(4, CP1, CP2, CEQ(6,1), COST(6))
CEQ(6,1) = COST(6) * IN18 / IN80
CEQ(7,1) = COND(1) * 18. / 1000. / 3.785 / 60.
CEQ(7,2) = COND(2) * 18. / 1000. / 3.785 / 60.
CEQ(7) = F7(CEQ(7,1)) + F7(CEQ(7,2))
CEQ(8,1) = HSHIF
CEQ(9,1) = LSHIF
CEQ(10,1) = SV * NS
CALL RLIN(13, CC1, CC2, CEQ(10,1), COST(10))
COST(10) = COST(10) * IN18 / IN80 * CKW
CEQ(11,1) = AIRC / 453.6 * 10.73 * 298. * 1.8 / 14.7 / 1.04 / 60.
COST(11) = F11(CEQ(11,1))
CAK = 0.
DO 2 K = 1, 11
2 CAK = CAK + COST(K)
DO 3 K = 1, 11
3 P(K) = COST(K) / CAK * 100.
READ(5, FACTR)
WRITE(6, FACTR)
OANDM = CKW * CMAIN * 24. * 365. + CAK * CREPL / MTIME + WATER
CWAT = MEAN FACTOR OF COOLING WATER FOR RECYCLE
READ(5, NENEG)
WRITE(6, NENEG)
ENPU = TOTAL INPUT FUEL, G-MOLE/HR
AVHT = AVERAGE HEATING VALUE OF INPUT FUEL, BTU/FT^3
C ENG: COST OF ENERGY FUEL, $/GJ

READ(5,ENG)

WRITE(6,ENG)

PO = ENPU/453.6*AVHT/1000000.*CENG*24.*365.

WRITE THE RESULTS

WRITE(6,103)

WRITE(6,101) ((KK,COST(KK),P(KK)),KK=1,11)

WRITE(6,102) CAK,CAW,OANDM,PO

C

C

WRITE(6,103)

WRITE(6,101) ((KK,COST(KK),P(KK)),KK=1,11)

WRITE(6,102) CAK,CAW,OANDM,PO

C

C

WRITE THE RESULTS

WRITE(6,103)

WRITE(6,101) ((KK,COST(KK),P(KK)),KK=1,11)

WRITE(6,102) CAK,CAW,OANDM,PO

C

C

READ(5,ENG)

WRITE(6,ENG)

R=(1-(TAX+TAXL))*FDXCD+FP*CP+FC*CC+FL*(1-(TAX+TAXL))*FD

CAKM: COST-OF-CAPITAL FACTOR

CAKM=EXP(.418*RXL)

CAKE: ESCALATION FACTOR

CAKE=EXP(.562*(EK+FL)*L)

CAPH: CAPITAL FACTOR

CAPH=1.03*CAPIT

TLIN: LEVELIZED LOCAL TAX AND INSURANCE

TLIN=0.03*CAPIT

CN: NON-ENERGY COST

CN=OANDM+TLIN

CRFRE: CAPITAL RECOVERY FACTOR AT R FOR ECONOMIC LIFE

C3=1

C4=0.

DO 5 I=1,NE
C3=C3/(1.+R)
C4=C4+C3
5 CONTINUE
CRFRE=1./C4
CRFRT: CAPITAL RECOVERY FACTOR AT R FOR TAX DEPRECIATION LIFE
D1=1.
D2=0.
DO 6 I=1; NT
DO 280200
D1=D1/(1.+R)
D2=D2+D1
6 CONTINUE
CRFRT=1./D2
D2=D2+D1
6 CONTINUE
CRFRT=1./D2
CRFRT: CAPITAL RECOVERY FACTOR AT R FOR TAX DEPRECIATION LIFE
D1=1.
D2=0.
DO 6 I=1; NT
DO 280200
D1=D1/(1.+R)
D2=D2+D1
6 CONTINUE
CRFRT=1./D2
C CEN: LEVELIZED ENERGY COST
C CEN=PO*XCRF/CRFRK
C DEP: LEVELIZED DEPRECIATION FACTOR FOR SUM OF YEARS DIGITS (SYD)
DEP = 2.*X(NT-1. )/(NT*(NT+1. )*R)
FCL: LEVELIZED FIXED CHARGES
FCl=CAPIT*XFCR+CEN
WRITE(6,104) DEP,FCl,CRFRE,CRFRK
WRITE(6,105) FCl,CEN,RLAC
101 FORMAT(IX,'COST(','I2,'=','E13.5,10X,F5.2)
102 FORMAT(/IX,'TOTAL CAPITAL COST(F.O.B)','E13.5/I1X,'TOTAL WORKING CA-
103 FORMAT(/IX,'LEVELIZED FIXED CHARGES ','E13.5/I1X,'LEVELIZED ENERGY COST -
104 FORMAT(' INFORMATION OF ECONOMIC FACTOR: '/)
105 FORMAT(' LEVELIZED FIXED CHARGES ','E13.5/I1X,'LEVELIZED ENERGY COST -
106 FORMAT(' FIXED CHARGE RATE ','F10.5/
C THIS SUBROUTINE IS TO CALL LINEAR INTERPOLATION.
C THE ALGORITHM REQUIRES XT VECTOR TO BE IN ASCENDING ORDER.
C
DIMENSION XT(20), YT(20)

I=2
IF(X.LE.XT(I)) GO TO 20
I=N
IF(X.GE.XT(N)) GO TO 20
DO 10 I=2,N
10 CONTINUE
AN X=YT(I-1)+(YT(I)-YT(I-1))/(XT(I)-XT(I-1))(X-XT(I-1))
RETURN

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Cost analysis of phosphoric acid fuel cell power plant includes two parts: a method for estimation of system capital costs, and an economic analysis which determines the levelized annual cost of operating the system used in the capital cost estimation. A FORTRAN computer program has been developed for this cost analysis.