

## SIMULATION AND ECONOMIC APPRAISAL OF ZEOLITE PRODUCTION SCHEMES FOR WATER TREATMENT

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### ABSTRACT

The selection of the most appropriate technology for the production of a specific compound requires the adoption of thorough technical and economic analysis to identify a preferred technology from a set of optional schemes. This work is concerned with the technical and economic analysis of the production of zeolite A which is widely used for several applications in general and as ion-exchanger in builders for detergents in particular. Two processes for the manufacture of zeolite A have been explored including: a) from reactive aluminosilicates gels or hydro gels and b) from kaolins. The adopted processes have been first well described on the basis of published patents and papers. Simulation has been conducted for the proposed schemes using HYSYS software package which has been adapted to handle inorganic compounds and solids. Engineering systems have been then developed through equipment selection and sizing for these schemes for typical production capacities within the range of 150 to 10000 tons /year. Economic evaluation has been undertaken for the proposed production schemes for the defined capacities range.. The profitability has been compared using the simple rate of return and sensitivity analysis has been undertaken

It is concluded that the use of natural materials for the production of zeolite A as detergent builder is recommended for technical and economic considerations.

**Keywords:** zeolite A, simulation, economic appraisal, HYSYS

## INTRODUCTION

Extensive efforts involving thorough technical and economic analysis are usually exerted to select the most appropriate technology for the production of a specific compound from a set of optional schemes. According to recent information, about 4 million tons of natural zeolites are consumed annually. However, due to its importance and wide use, zeolites have been synthesized with tailored structure enabling specific properties and application. More than 600 types have been developed. The consumption of synthetic zeolites approaches 1.4 million tons annually. The largest amount of synthetic zeolites is used as ion-exchanger (water softener) in builders for detergents. Zeolites are crystalline hydrated aluminosilicates which are based on an infinitely extending three dimensional network of  $\text{AlO}_4(-5)$  and  $\text{SiO}_4(-4)$  tetrahedra linked to each other by sharing all of the oxygen. The specific functional properties of zeolite enable its use in various applications including adsorption, catalysis, water treatment, and molecular sieving. . Within the last 30 years, zeolites replaced most phosphates and complexing agents for detergents. Detergent builders are high performance materials which contain about 15-25% of zeolite [1]

Processes for the manufacture of zeolites may be classified into two main approaches [2]:

1. The preparation of zeolites as high purity crystalline powders or as performed pellets from reactive aluminosilicate gels or hydro gels.
2. The conversion of clay minerals, kaolin in particular, into zeolites either in the form of high purity powders or as binder less high purity performed pellets.

Despite extensive publications on zeolite preparation, investigations are being

conducted along several directions to prepare new zeolites with specific properties, investigate the effects of various raw materials and additives, vary the operating conditions, and employ special equipment to produce a specific zeolite.

Several authors recently investigated the conditions for zeolite production from pure materials. Richard, et.al. [3], synthesized zeolite A of 0.1-0.7 microns crystal size, 1-5 microns particle size by mixing sodium aluminate and sodium silicate solutions to perform the aluminosilicate synthesis gel followed by crystallization. Controlling the amount of sodium aluminate and the presence or absence of seeds affects the formation of zeolite A.

Bronic, et al. [4], studied the mutual interactions between zeolite A seed crystal, added to a clear aluminosilicate solution (seed-side), and an amorphous aluminosilicate gel (gel-side), by crystallization of zeolite A. It was concluded that the crystallization of zeolite A in the gel-side of the reactor occurs by the growth of nuclei released from the gel dissolved during the crystallization. Other work on zeolite preparation with [3],[5],[6] or without [7], [8], [9] the use of seed crystals has been recently patented or published

On the other hand, clays have been used by several authors to synthesize different zeolites. Early authors mentioned applying crystallization for long periods to reach 7 days. In an attempt to reduce the crystallization time, Jameson, et. al. [10], used kaolin clay, chlorine and sodium hydroxide to produce white crystals zeolite A, and, it was indicated that crystallization took about 5 hours.

Processes involving treatment of waste, recovery of some species and recycling others were developed with different raw material; Ramon, et. al. [11], used bauxite to synthesize 4A zeolite by digesting bauxite at 90 °C -100 °C using 11% NaOH solution,

filtration and reacting the filtrate at 60 °C -70 °C with alkaline solution of silica then crystallizing the formed gel to produce the desired zeolite.

Research also tends to improve the prepared zeolite properties; Chandrasekhar et.al. [12], used kaolin to synthesize 4A zeolite discussing the ways to improve its brightness. Other work on using clays for synthesis of zeolite A has been recently published. [10]- [15].

To select the appropriate scheme extensive technical assessment should be firstly undertaken. Over the last decades, significant advances in process modeling and simulation have been achieved. Various process-simulation systems with advanced capabilities have been developed to enable the technical assessment through the provision of maximum information about the process from minimum input data. Further the simulation system provides reliable estimates of equipment sizing, heating and cooling loads, temperature, and levels of heat rejection and power requirements that would enable reliable estimation of plant cost. [16]- [18]

This work is dedicated to the simulation and cost analysis of zeolite A production schemes to come up with the optimum recommended scheme under prevailing conditions and constraints.

## **APPROACH AND METHODOLOGY**

The adopted approach involved the following:

### **1. Process Description**

Identification of integrated schemes for zeolite A production, through analysis of the optional production schemes, has been undertaken based on published information. Although extensive information is published, limited detailed quantitative data is

available on the various processing stages involving quantities of input and output components of the various processing stages. However, through the available information, it has been possible to identify and formulate integrated schemes for two cases involving the use of pure materials or natural materials. Within the scope of this work, capacities in the range between 150 and 10000 ton/year have been investigated.

## **2. HYSYS Simulation**

Simulation has been conducted for the proposed schemes using HYSYS flowsheeting software version 2.1 [19]. Although this software has been initially designed to simulate systems involving liquids, it has been possible to adopt HYSYS for the simulation of zeolite production.

## **3. Engineering Development & Economic Appraisal**

For the purpose of techno-economic assessment of the proposed schemes, engineering systems for the defined range of capacities have been developed. Further, economic evaluation has been undertaken, profitability has been compared using the simple rate of return and sensitivity analysis has been conducted.

## **PROCESS SCHEMES FOR ZEOLITE A PRODUCTION**

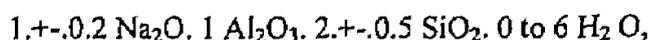
Two optional schemes for Zeolite A production have been identified as outlined below

### **Case 1: Process Comprising Use of Pure Materials**

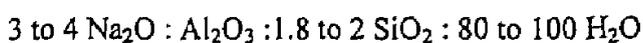
This process depends on producing zeolite A from pure materials by mixing sodium aluminate dissolved in water with sodium silicate dissolved in water, in the presence of sodium hydroxide solution at a ratio by weight corresponding to a calculated total composition with respect to the molar ratios of

1.8 to 6 Na<sub>2</sub>O : 1 Al<sub>2</sub>O<sub>3</sub> : 1 to 2.4 SiO<sub>2</sub> : 50 to 300 H<sub>2</sub>O

The chemical composition of the zeolite of the type NaA corresponds to the molecular formula



The formed sodium aluminosilicate gel is maintained for at least 10 minutes at a temperature in the range from 70 °C to 95 °C, with agitation, until the formation of a crystalline sodium aluminosilicate of the type NaA with a molar ratio of  $\text{SiO}_2 : \text{Al}_2\text{O}_3$  from 1.8 to 2.2 and a mean particle size of less than 3 microns. In this form of the product, the calculated total composition of the two solutions to be reacted is preferably adjusted so that it corresponds to molar ratios of



Through receivers, the two liquid components are transported to the gel reactor. The amorphous sodium aluminosilicate gel obtained is subjected to subsequent crystallization by heating the gel prior to filtration, with or without agitation, to a temperature in the range from 70°C to 95 °C. and maintaining this temperature until crystallization occurs.

Depending on the amount of flow, the crystallization of the amorphous gel is suitably performed in separate crystallizing vessels. The crystallization temperature can be adjusted by jacket heat as well as by direct blowing in of steam.

The optimal duration of the crystallization time is about 4 hours. The crystallization is ends when the desired product has reached its maximal calcium-binding capacity. The resulting amorphous sodium aluminosilicate precipitates are subsequently crystallized under defined crystallization conditions. Then zeolite A crystals are filtered, washed to be freed from excess alkali and dried.

## **Case 2: Process Comprising Use of Natural Materials**

This process is directed towards synthesis of hydrated alkali metal silicate ion-exchange material in the form of white crystals using discolored iron-contaminated naturally occurring kaolin clay as a source of alumina and silica. It is well known that sodium zeolite A can be obtained at relatively low cost by using minerals as sources of silica and/or alumina. Kaolin clay is calcined to the so-called "metakaolin" state or condition [19]. When the clay is calcined and then used as a reactant in the synthesis of a zeolitic aluminosilicate, the iron becomes finely disseminated throughout the crystalline reaction product and has a discoloring effect that is materially more pronounced than when such impurities were originally occluded in the structure of the clay particles. Based on this hypothesis and the discovery that iron impurities in clay, that cannot be removed by conventional methods, is especially amenable to removal by volatilization as a chloride when the clay is calcined to so-called "metakaolin" state or condition, a method for producing high purity synthetic metal-aluminosilicates from calcined kaolin has been used.

An essential feature of this process resides in chlorinating the kaolin clay in a gas-solid reaction after the clay has been calcined at a temperature between 600°C- 980°C and time such that the dehydrated clay is in the form of metakaolin but before the metakaolin is reacted with caustic to synthesize the zeolite crystals. Volatilization of iron from the zeolite crystals would destroy the crystals if in fact efficient removal could be effected. Still another essential feature resides in controlling the temperature of the clay during calcination and chloridization as described above in order to secure both efficient removal of iron by volatilization while providing the calcined clay a state or condition

such that it is reactive with caustic to produce the desired synthetic crystalline sodium aluminosilicate.

The iron content of a typical bleached, beneficiated soft kaolin clay (expressed as  $\text{Fe}_2\text{O}_3$ ) is generally in the range of about 0.2 percent to 0.3 percent based on the weight of the clay after being calcined to anhydrous condition at  $980^\circ\text{C}$ .

For economic reasons, it is preferable not to cool the clay between calcination and chloridization. Suitable chloridizing agents known include chlorine, hydrochloric acid and carbon tetrachloride. A carbonaceous material such as carbon monoxide or carbon may be introduced during chlorination to accelerate the formation of iron chlorides. Preferably chloridization is carried out at a temperature above  $600^\circ\text{C}$  with an upper limit of about  $980^\circ\text{C}$  in order to achieve sufficiently rapid reaction and prevent local overheating. Preferably, the  $\text{Fe}_2\text{O}_3$  analysis of the chloridized clay is below 0.1 % by weight. The treated clay is cooled to at least a temperature below about  $100^\circ\text{C}$  before it is used as a reactant to form zeolite crystals.

After crystallization of the desired sodium aluminosilicate is completed, the crystals should be washed free of alkali and dried mildly, at a temperature of about  $100^\circ\text{C}$ .

## HYSYS SIMULATION

HYSYS interactive modeling and simulation software has a powerful simulation environment providing the capability to deal with an entire process as completely and accurately as possible. It contains library of components and their physical and thermodynamic properties, variety of unit operations and processes, possibility to

calculate accurately recycle streams which are usually present in any industrial flow sheet and also nearly impossible to fix manually.

However, the studied cases use inorganic materials, some of which are solids. HYSYS has been mainly developed for liquid petroleum compounds and does not have most of these inorganic solids in its own library. This problem has been overcome through *hypotheticals* section, through which HYSYS allows creation of non-library or hypothetical components.

Hypothetical components may be pure components, defined mixtures or solids. A wide selection of estimation methods is provided for the various Hypo groups (hydrocarbons, alcohols, etc...) to ensure the best representation of the behavior of the hypothetical component in the simulation.

Thus, within the scope of this research, it deemed necessary to provide almost every physical and thermodynamic property of each component in HYSYS *hypotheticals* section so that it can identify this component and deals with it properly in the following simulation stages. Thus it has been possible to make use of HYSYS with its powerful environment to simulate specific non conventional processes.

The unit operations: crystallizer and dryer are conventional physical unit operations in chemical industry, but they are not included in HYSYS unit operations library. This problem has been solved by adopting HYSYS unit operations to achieve the required simulation performance. From the literature, crystallization of zeolites is considered to have first order reaction kinetics, with or without mixing, and is conducted in a separate vessel. So a plug flow reactor was chosen from HYSYS units. Following the same logic, a conversion reactor was selected to operate at 100°C to convert wet zeolite crystals to

dry zeolite and expel the accompanying water. Testing results in each step is necessary in order to ensure proper simulation.

## **ENGINEERING DEVELOPMENT**

### **a. Equipment Selection and Sizing**

The material and energy balance requirements are estimated on a preliminary basis using EXCEL spreadsheet and through extensive simulation of the proposed schemes using HYSYS flow sheeting program. Equipment selection and sizing has been conducted for the proposed schemes.

### **Operating Requirements**

According to the proposed production scheme the operating requirements have been identified for the basic production capacity of 150 tpy and has been extrapolated for other potential capacities namely 1500 tpy, 6000 tpy, 10000 tpy which are typical for commercial plants. The principal operating requirements include the raw materials, labour and utilities comprising steam, cooling & process water, electricity and fuel.

## **ECONOMIC APPRAISAL**

### **a. Purchased Equipment Cost**

Since the aim of this work is to identify the appropriate scheme for zeolite A production at early phases of development, the major equipment costs are estimated according to published equipment cost data from various sources as outlined below.

### **b. Cost Functions**

Costs of major equipment are published in the form of figures relating the price to a specific major parameter that is controlling for each type of equipment. The cost functions were used to determine the equipment cost for the major equipment in the

production schemes for the capacities investigated namely 150 tpy zeolite NaA, and up to 10000 tpy, representing the typical worldwide commercial production. Cost functions were derived, within the scope of this work, from the published cost data for each equipment type. The Marshall and Swift equipment cost index is used to calculate the costs of 2003. Detailed results are provided elsewhere [20].

#### **c. Estimation of Fixed-Capital Investment**

The fixed-capital investment estimate has been estimated using the study (factored) estimate method. Items of the fixed capital investment have been estimated as a factor of the purchased equipment cost as presented in Table (1)

#### **d. Total Operating Costs**

Operating costs include raw materials, utilities, labor, maintenance and repair, laboratory, and plant overhead.

#### **e. Depreciation**

While several alternative methods may be used for determining the rate of depreciation, in this research, the straight-line method with an average life time of 15 years and negligible salvage has been assumed.

#### **f. Revenues**

According to the current international market price and guided by actual reported costs of imported zeolite A, it has been assumed through the scope of this research that the selling price of zeolite A is 660 \$/ton .

## **RESULTS AND DISCUSSION**

### **Results of Case 1: Production of zeolite A from Pure Materials**

HYSYS simulation results identify the over all process flow diagram for the simulated process showing all the unit operations and processes ( Figure (1)), material streams inputs & outputs involving their operating conditions ( Table (2)), compositions of all the material streams inputs & outputs ( Table (3)).

### **Results of Case 2: Production of Zeolite A from Natural Materials**

Similar HYSYS results have been obtained for Case 2. Several other intermediate results could be obtained from HYSYS flow sheeting Software.

### **Economic Appraisal**

#### **a. Cost Analysis**

##### **1. Equipment Cost**

Total major equipment cost for each production scheme selected and production capacities were determined. Accordingly the Capital Investments have been estimated

#### **b. Investment, Production Costs, and Profitability**

Figure (2) represents investment, production costs, and profitability results for cases 1 and 2 respectively at the different production capacities

The following comments may be set forth:

##### **a- Capital Investment**

- According to the assumptions and estimates, the capital investment is lowest for case 1 which is based on the use of pure materials. About \$ 392 thousands and \$ 9.6 millions are the estimated capital costs for the 150 tpy and 10000 tpy production capacities respectively.

- Corresponding capital investment for 150 tpy are \$ 449 thousands for case 2.
- Highest estimated capital cost is about \$ 12.4 millions for case 2 at 10000 tpy production capacity.

#### b- Operating Costs

- At 150 tpy, the annual operating costs have been estimated as \$ 102 thousands and \$ 69 thousands for cases 1 and 2 respectively.
- The raw material costs are the major cost item for case 1 representing 49% and 69% of the total production costs for 150 tpy and 10000 tpy respectively.
- Despite lowest capital investment for case 1, its total production cost exceeds the corresponding values for case 2 for all capacities. This increase is due to the higher operating costs resulting from high raw material costs.

#### c- Profitability

- Revenues have been estimated for all cases and production capacities at \$660/ton zeolite A.
- For case 1 production costs exceed revenues for the 150 tpy and 1500 tpy. For higher capacities, profit is generated but the simple rate of return (SRR) is around 4% for the 10000 tpy production capacity.
- For case 2, SRR varies between 0.2% for the lowest capacity and exceeds 20% for the 10000 tpy production capacity.

### **Optimum Production Capacity**

For the two investigated cases, the SRR vs. production capacities have been plotted as presented in figure (3). The current interest rate and discount factor for the US\$ is about

2.5%. Thus the minimum production capacities are about 5870 and 244 ton/yr for cases 1 and 2 respectively

## CONCLUSIONS & RECOMMENDATIONS

In view of the findings of this work, the following conclusions and recommendations may be set forth

- Adopted system engineering approach provides conclusive results to support decision making regarding the selection of optimal technological scheme for chemical processes,
- A hierarchical approach integrating internet, data bases, spreadsheets, engineering software, and cost data permits extensive technical and economical analysis of integrated chemical process schemes,
- HYSYS simulation software could be adopted to handle additional inorganic components and operations,
- The use of natural materials, although requiring relatively higher capital investments, has higher profitability as expressed by the Simple Rate of Return which has been estimated, within the scope of this work, to be about 0.22% and 20.3% for production capacities of 150 tpy and 10000 tpy respectively. On the other hand, on starting with pure materials much lower Simple Rate of Return could be achieved with a maximum of 4% for the 10000 tpy production capacity.
- It is concluded that the use of natural materials for the production of zeolite A as detergent builder, which has been the subject of this work, is recommended for technical and economic considerations.

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*Table (1) Ratio Factors for Estimating Fixed-Capital Investment Items Based on Delivered Major Equipment Cost Used for Zeolite NaA Production.*

| Item  | Percent of delivered equipment cost for solid-fluid-processing plant |
|---|--|
| Purchased equipment-delivered                                     | 100  |
| Auxiliary Equipment   | 20   |
| Purchased-equipment installation                                  | 15   |
| Transportation  | 15   |
| Instrumentation and controls (installed)                          | 10   |
| Piping (installed)  | 15   |
| Electrical (installed)  | 8  |
| Buildings (including services)                                    | 20   |
| Service facilities ( installed)                                   | 20   |
| <i>Total direct plant cost</i>                                    | 223  |
| Engineering and supervision                                       | 20   |
| Construction expenses   | 20   |
| <i>Total direct and indirect plant cost</i>                       | 263  |
| Contractor's fee ( about 5-6% of direct and indirect plant costs) | 13   |
| Contingency (about 8-10% of direct and indirect plant costs)      | 24   |
| <i>Fixed-capital investment</i>                                   | 300  |

Table (2) Material Streams in & out Conditions, CASE 1

| Workbook - Case (Main)    |              |             |            |              |             |
|---------------------------|--------------|-------------|------------|--------------|-------------|
| Na aluminate              |              |             |            |              |             |
| Name                      | Na aluminate | Na silicate | H2O        | Reactor Vent | Reactor Out |
| Vapour Fraction           | 0.0000       | 0.0000      | 0.0000     | 1.0000       | 0.0000      |
| Temperature [C]           | 25.00        | 25.00       | 25.00      | 75.00        | 75.00       |
| Pressure [kPa]            | 101.4        | 101.4       | 101.4      | 101.4        | 101.4       |
| Molar Flow [kgmole/h]     | 0.06281      | 0.06285     | 6.279      | 0.0000       | 0.06921     |
| Mass Flow [kg/h]          | 15.36        | 11.85       | 113.1      | 0.0000       | 140.3       |
| Liquid Volume Flow [m3/h] | 0.003318     | 0.005591    | 0.1133     | 0.0000       | 0.1152      |
| Heat Flow [kJ/h]          | -7.130e+04   | -1.009e+05  | -1.793e+06 | 0.0000       | -2.075e+06  |
| Name                      | Cryst. Feed  | Cryst.Out   | Water 1    | Cooler Out   | Mixer Out   |
| Vapour Fraction           | 0.0000       | 0.0000      | 0.0000     | 0.0000       | 0.0000      |
| Temperature [C]           | 74.52        | 82.22       | 25.00      | 30.00        | 27.78       |
| Pressure [kPa]            | 101.3        | 253.3       | 101.3      | 101.3        | 101.3       |
| Molar Flow [kgmole/h]     | 0.1478       | 4.024       | 3.972      | 4.024        | 7.996       |
| Mass Flow [kg/h]          | 145.1        | 145.1       | 71.55      | 145.1        | 216.6       |
| Liquid Volume Flow [m3/h] | 0.1189       | 0.1247      | 0.07169    | 0.1247       | 0.1964      |
| Heat Flow [kJ/h]          | -2.149e+06   | -2.283e+06  | -1.134e+06 | -2.331e+06   | -3.465e+06  |
| Name                      | F1.Vent      | F1.Liquid   | F1.Solids  | F.Solids     | to Recycle  |
| Vapour Fraction           | 0.0000       | 0.0000      | 0.0000     | 0.0000       | 0.0000      |
| Temperature [C]           | 27.78        | 27.78       | 27.78      | 27.78        | 27.78       |
| Pressure [kPa]            | 101.3        | 101.3       | 101.3      | 101.3        | 101.3       |
| Molar Flow [kgmole/h]     | 0.0000       | 6.421       | 1.575      | 1.496        | 0.07876     |
| Mass Flow [kg/h]          | 0.0000       | 121.5       | 95.16      | 90.40        | 4.758       |
| Liquid Volume Flow [m3/h] | 0.0000       | 0.1217      | 0.07467    | 0.07094      | 0.003734    |
| Heat Flow [kJ/h]          | 0.0000       | -1.967e+06  | -1.498e+06 | -1.423e+06   | -7.491e+04  |
| Name                      | R.Crystals   | F2.Feed     | Water 2    | F2.Vent      | F2.Liquid   |
| Vapour Fraction           | 0.0000       | 0.0000      | 0.0000     | 0.0000       | 0.0000      |
| Temperature [C]           | 27.78        | 25.13       | 25.00      | 25.13        | 25.13       |
| Pressure [kPa]            | 101.3        | 101.3       | 101.3      | 101.3        | 101.3       |
| Molar Flow [kgmole/h]     | 0.07860      | 45.63       | 44.13      | 0.0000       | 44.06       |
| Mass Flow [kg/h]          | 4.748        | 885.4       | 795.0      | 0.0000       | 795.0       |
| Liquid Volume Flow [m3/h] | 0.003724     | 0.8675      | 0.7966     | 0.0000       | 0.7966      |
| Heat Flow [kJ/h]          | -7.476e+04   | -1.402e+07  | -1.260e+07 | 0.0000       | -1.261e+07  |
| Name                      | F2.Solids    | Dryer Vent  | PRODUCT    | ** New **    |             |
| Vapour Fraction           | 0.0000       | 1.0000      | 0.0000     |              |             |
| Temperature [C]           | 25.13        | 100.0       | 100.0      |              |             |
| Pressure [kPa]            | 101.3        | 101.3       | 101.3      |              |             |
| Molar Flow [kgmole/h]     | 1.566        | 3.765       | 0.06298    |              |             |
| Mass Flow [kg/h]          | 90.40        | 67.87       | 22.53      |              |             |
| Liquid Volume Flow [m3/h] | 0.07094      | 0.06801     | 0.03614    |              |             |
| Heat Flow [kJ/h]          | -1.414e+06   | -9.031e+05  | -3.356e+05 |              |             |

Material Streams Compositions Energy Streams Unit Ops

Table (3) Material Streams in & out Compositions, CASE 1

| Workbook - Case (Main)        |              |             |           |                     |             |
|-------------------------------|--------------|-------------|-----------|---------------------|-------------|
| Na aluminate                  |              |             |           |                     |             |
| Name                          | Na aluminate | Na silicate | H2O       | Reactor Vent        | Reactor Out |
| Comp Mole Frac (Na aluminat*) | 1.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0009      |
| Comp Mole Frac (Na silicate*) | 0.0000       | 1.0000      | 0.0000    | 0.0000              | 0.0009      |
| Comp Mole Frac (Z.A.*)        | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (NaOH*)        | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (gel*)         | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.9070      |
| Comp Mole Frac (H2O)          | 0.0000       | 0.0000      | 1.0000    | 1.0000              | 0.0912      |
| Comp Mole Frac (zeolite cry*) | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Name                          | Cryst. Feed  | Cryst. Out  | Water 1   | Cooler Out          | Mixer Out   |
| Comp Mole Frac (Na aluminat*) | 0.0004       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Na silicate*) | 0.0004       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Z.A.*)        | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (NaOH*)        | 0.0209       | 0.0809      | 0.0000    | 0.0809              | 0.0407      |
| Comp Mole Frac (gel*)         | 0.4249       | 0.0002      | 0.0000    | 0.0002              | 0.0001      |
| Comp Mole Frac (H2O)          | 0.5311       | 0.9026      | 1.0000    | 0.9026              | 0.9510      |
| Comp Mole Frac (zeolite cry*) | 0.0221       | 0.0162      | 0.0000    | 0.0162              | 0.0082      |
| Name                          | F1.Vent      | F1.Liquid   | F1.Solids | F.Solids to Recycle |             |
| Comp Mole Frac (Na aluminat*) | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Na silicate*) | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Z.A.*)        | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (NaOH*)        | 0.0407       | 0.0411      | 0.0394    | 0.0394              | 0.0394      |
| Comp Mole Frac (gel*)         | 0.0001       | 0.0000      | 0.0005    | 0.0005              | 0.0005      |
| Comp Mole Frac (H2O)          | 0.9510       | 0.9589      | 0.9186    | 0.9186              | 0.9186      |
| Comp Mole Frac (zeolite cry*) | 0.0082       | 0.0000      | 0.0415    | 0.0415              | 0.0415      |
| Name                          | R.Crystals   | F2.Feed     | Water 2   | F2.Vent             | F2.Liquid   |
| Comp Mole Frac (Na aluminat*) | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Na silicate*) | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (Z.A.*)        | 0.0000       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (NaOH*)        | 0.0394       | 0.0013      | 0.0000    | 0.0013              | 0.0013      |
| Comp Mole Frac (gel*)         | 0.0004       | 0.0000      | 0.0000    | 0.0000              | 0.0000      |
| Comp Mole Frac (H2O)          | 0.9185       | 0.9973      | 1.0000    | 0.9973              | 0.9987      |
| Comp Mole Frac (zeolite cry*) | 0.0416       | 0.0014      | 0.0000    | 0.0014              | 0.0000      |
| Name                          | F2.Solids    | Dryer Vent  | PRODUCT   | ** New **           |             |
| Comp Mole Frac (Na aluminat*) | 0.0000       | 0.0000      | 0.0010    |                     |             |
| Comp Mole Frac (Na silicate*) | 0.0000       | 0.0000      | 0.0010    |                     |             |
| Comp Mole Frac (Z.A.*)        | 0.0000       | 0.0000      | 0.9858    |                     |             |
| Comp Mole Frac (NaOH*)        | 0.0012       | 0.0005      | 0.0000    |                     |             |
| Comp Mole Frac (gel*)         | 0.0005       | 0.0000      | 0.0121    |                     |             |
| Comp Mole Frac (H2O)          | 0.9586       | 0.9995      | 0.0000    |                     |             |
| Comp Mole Frac (zeolite cry*) | 0.0396       | 0.0000      | 0.0001    |                     |             |

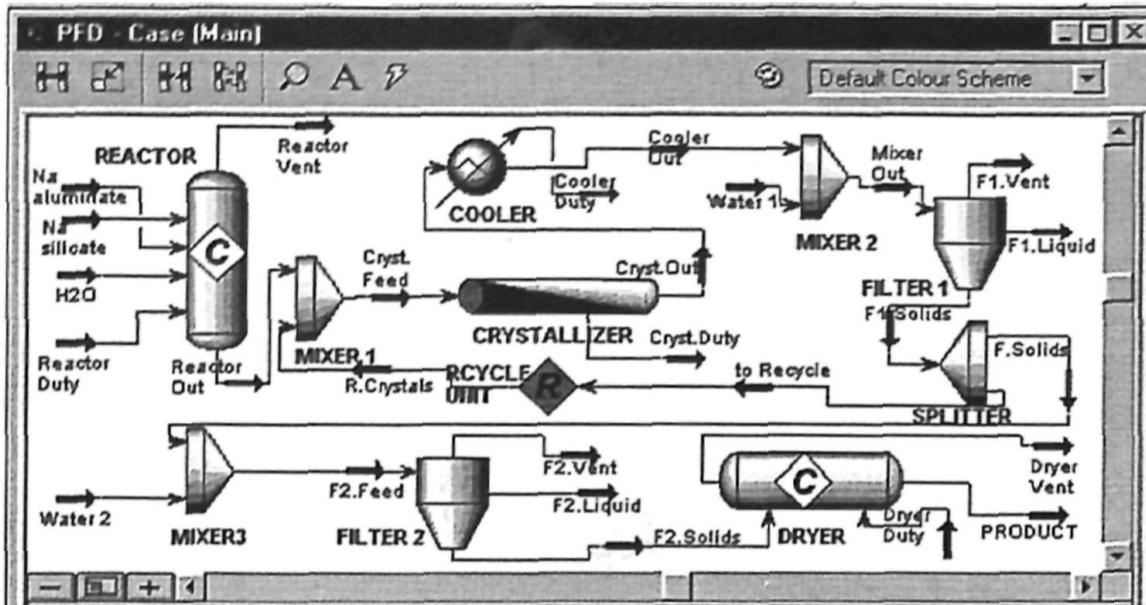


Fig. (1) HYSYS Process Flow Diagram, Case 1

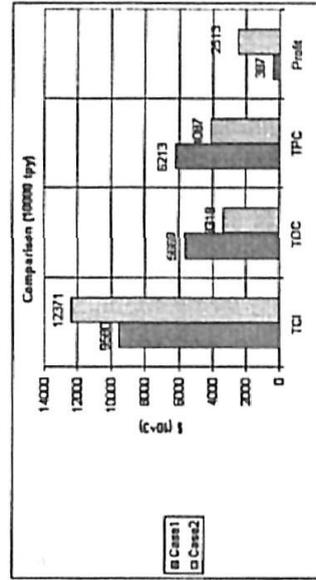
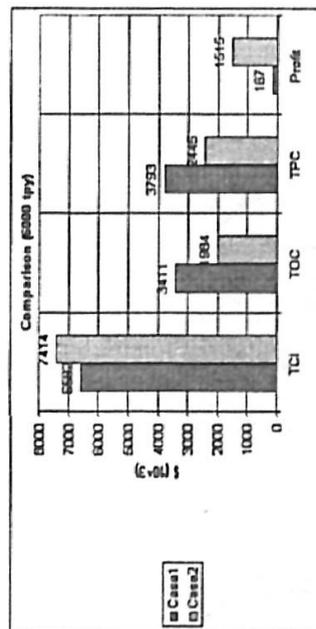
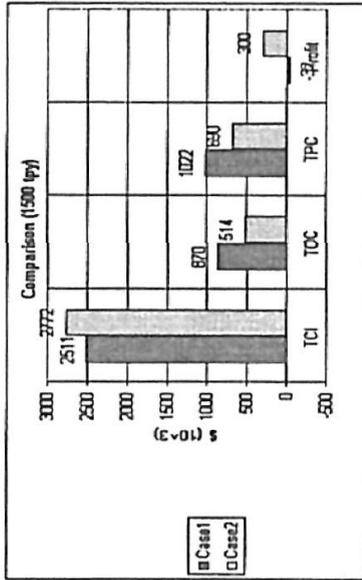
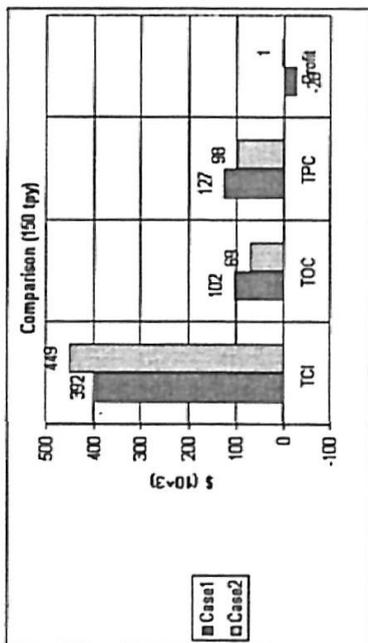


Figure (2) Comparison between the two schemes: total capital investment (TCI), total operating costs (TOC), total production costs (TPC) and profit for different production capacities

