A MULTIPLE MICROPROCESSOR NETWORK FOR ENERGY SYSTEM MODELLING AND ANALYSIS

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ABSTRACT

A multiple microprocessor network that simulates a large-scale energy production system has been developed. Each microprocessor in the network with its associated memory phases represents a stage of an energy resource production cycle, such as extraction, processing, or transportation. These memory phases consist of random access memories that store the inputs, outputs, and defining parameters for their associated energy production stages and provide the means of communication between stages. There is a microprocessor with an attached memory that contains its program instructions between every memory phase for each energy resource that is being processed. These processors operate independently and execute the necessary simulation operations. This network is a special purpose multiple-processor computer which implements a model used to analyze the relationship between the energy production system's efficiency and societal impact.

I. Introduction

The realization of the scarcity of various energy resources and the need to develop new sources of energy has stimulated interest in formulating a comprehensive energy policy by government and industry. This policy would take into consideration the availability of existing energy resources and new energy technologies as well as the impact this policy would have on society. The purpose of this paper is to present a multiple microprocessor network that simulates a large-scale energy production system that can be used to evaluate various energy policy alternatives. This computer system can be used to model industrial, regional, national, or international energy production systems so that a plan can be evaluated at any one of these levels.

When formulating an energy policy it is important to consider the dependency the development of an energy resource has on the supply of other sources of energy in the system. For example, in order to use solid wastes as a fuel source, petroleum is needed to transport the wastes to a site where they can be processed. This increased energy use within the energy production system decreases the availability of this energy outside the system. Changes in the amount and method of production of a given energy resource will induce changes in production and societal impacts of the other energy resources that are being processed. In order to evaluate these changes, an analysis of the energy production system must include the processing of all possible energy sources and their interaction. This may include such diverse sources of energy as fossil fuels (which include petroleum, coal, natural gas and oil shale), water power, nuclear power, solar energy, wind power, tidal energy, geothermal power, magnetohydrodynamic generation, solid wastes, and hydrogen. This dependency within the energy production system is an important factor in determining the system's overall efficiency.

In addition to evaluating the energy production system's efficiency, the impact that any energy policy has on society should be measured. An obvious impact that energy production and consumption has had on society is environmental pollution. However, energy policy will also determine such things as energy dependency on other countries, employment opportunities in impacted areas, and energy prices in affected regions.

Mathematical modelling and computer techniques can provide useful methods for formulating an energy policy. Mathematical models that describe the energy production system including the interaction of the generation of the various types of energy are helpful for evaluating alternative energy policies and their societal impact. Computers can be used in conjunction with these models to perform necessary calculations and to simulate the developed model.

The development of large-scale integrated circuits has greatly reduced the cost and size of computer hardware components making it economically possible and technically feasible to construct specialized computers consisting of many processor and memory elements. These factors have created the need for formal techniques that can be used to design such computer systems [1,2]. In answer to this need, a multiple microprocessor network has been developed to provide a general structure that can be used to construct multiple microprocessor systems. This structure and its defining equations are presented in part II this paper. In part III a large-scale energy production system model [3] that includes the dependency that energy resource development has on various sources of energy and the impact this development has on society is described. The model has a set of interconnected energy chains, each consisting of a cascade of stages which describe the processing of a resource to obtain energy of a given type. The interconnections implement the processing laws at a given stage which require energy inputs from other stages as well as the resources being processed. The multiple microprocessor network and its defining equations are then used to construct the large-scale energy production system in part IV. The model includes the entire set of energy chains and their interaction. After entering the values of the system parameters and the amount of each energy resource to be processed, the network will calculate the amount of each type of energy and pollutants, etc., generated so that the relationships between the energy production system's efficiency and environmental impact can be determined.

II. The Multiple Microprocessor Network

A multiple microprocessor network (MMN) has been developed to provide a general structure that can be used to construct systems composed of many microprocessor and memory elements. The motivation for this structure came from work that was done with charge-routing networks that were formulated to provide synthesis procedures for signal processing systems made from charge-coupled devices [4]. The MMN consists of semiconductor memories and microprocessor units connected in a specified arrangement to perform a computational function. The network is a tightly coupled multiple-processor system [1] with groups fo microprocessors sharing memory and address and data busses. Intermediate and final results of the operations performed progress through the many phases of memories in the network as in a pipeline computer organization [5].

The MMN contains the following types of memory elements:

(1) Input random access memories (INRAM) that contain the inputs to the system.
(2) Output random access memories (OUTRAM) that contain the outputs of the system.
(3) Intermediate random access memories (INTRAM) that contain the intermediate results of the operations performed by the system.
(4) Parameter random access memories (PARAM) that contain system parameter values.
(5) Read only memories (ROM) that contain the instructions that direct the microprocessors.

When constructed with presently available semiconductor memories, the contents of all the random access memories (RAM) is lost when their supply of power is removed. On the other hand, the ROM does not lose its contents when power is removed.

Fig. 1 shows the general structure we wish to discuss. In it one ROM and PARAM is connected to each microprocessor in the network. The ROM contains the program to be implemented by its associated microprocessor and the PARAM contains parameter values that can be used by the microprocessor while executing the program and define the system being implemented by the network. Having these parameter values in a RAM allows them to be changed and for some systems it may be desireable to modify these values based on results obtained in the network. The remaining RAM's of the system, INRAM's, OUTRAM's, and INTRAM's, are divided into the phases of Fig. 1 where any phase p, ranging from 0 to P, can contain all of these three types of RAM. A more general structure could allow information to be exchanged between any two phases of memory but only this structure that allows information to progress from one phase to its following phase will be considered here.

The memory phases are connected with microprocessors that perform the required processing on the data in the RAM's. The network can be constructed with one particular microprocessor or a variety of microprocessors. The microprocessors must be capable of 1) addressing all the words of their associated memories and 2) operating on data words equal in width to the memory word width. However, it would be desireable to use the same microprocessor throughout the network in order to have hardware modularity. The operations that can be performed at the branches of the MMN will depend upon the microprocessor selected for the system. Additional arithmetic capability can be added by attaching arithmetic units to the microprocessors [6]. All of the microprocessors in the network can be active at one time or selected microprocessors may operate independently. The processor unitd obtain the data needed to perform the required computations from the INTRAM's and INRAM's of its input memory phase and store the results in the INTRAM's and OUTRAM's of the following memory phasd. Only one microprocessor will supply data to either an OUTRAM or INTRAM but any microprocessor can use the data in an INRAM or INTRAM. However, the system has to be designed so that a location in an INTRAM is not altered by a microprocessor that provides it with data before a microprocessor that needs that data uses it.

The integer valued variable T represents the transition times with the difference between two successive T's representing the interval in true time during which the microprocessors carry out their calculations. We will assume that at the time represented by T + 1 the microprocessors have completed the execution of their programs as initiated at the time represented by T. The transition from one value of T to the next represents one processing cycle. Consequently, from this point on we refer to T as <u>time</u>.

Each memory phase of the MMN will have the following RAM memories:

n INTRAM's
m INRAM's
r OUTRAM's

where $0 \le n \le N$, $0 \le m \le M$, and $0 \le r \le R$ for any given phase. The following data is present in the memory locations at time T:

$x_k^i(T)$ = the data contained in the kth INTRAM of phase i at time T.
$u_k^i(T)$ = the data contained in the kth INRAM of phase i at time T.
$y_k^i(T)$ = the data contained in the kth OUTRAM of phase i at time T.

For each phase the data in all of the INTRAM's, all of the INRAM's, and all of the OUTRAM's can each be combined to form the following three column vectors:

$$\underline{X}^i(T) = \begin{bmatrix} x_1^i(T) \\ x_2^i(T) \\ \vdots \\ x_n^i(T) \end{bmatrix} \qquad \text{an n-vector of data}$$

$$\underline{U}^i(T) = \begin{bmatrix} u_1^i(T) \\ u_2^i(T) \\ \vdots \\ u_m^i(T) \end{bmatrix} \qquad \text{an m-vector of data}$$

$$\underline{Y}^i(T) = \begin{bmatrix} y_1^i(T) \\ y_2^i(T) \\ \vdots \\ y_r^i(T) \end{bmatrix} \qquad \text{an r-vector of data}$$

More than one data value may be present in any of the memories of a phase so any of the column vectors described above may be a vector of vectors. For example, $\underline{Y}^i(T)$ may be an r-vector of vectors. In order to represent the processing that takes place between memory phases the following matrices are defined:

$\underline{A}^i$ – a matrix that transforms the data in the INTRAM's of phase i to obtain the values stored in the INTRAM's of phase i + 1; of variable size, nxn if data is scalar.

$\underline{B}^i$ – a matrix that transforms the data in the INRAM's of phase i to obtain the values stored in the INTRAM's of phase i + 1; of variable size, nxm if data is scalar.

$\underline{C}^i$ – a matrix that transforms the data in the INTRAM's of phase i to obtain the values stored in the OUTRAM's of phase i + 1; of variable size, rxn if data is scalar.

$\underline{D}^i$ – a matrix that transforms the data in the INRAM's of phase i to obtain the values stored in the OUTRAM's of phase i + 1; of variable size, rxm if data is scalar.

Using the MMN to implement a linear time-invariant system, the following equations represent the data processing operations that occur between any two phases, i and i + 1, in the network where i = 0, ..., P-1:

$$\underline{X}^{i+1}(T+1) = \underline{A}^i\, \underline{X}^i(T) = \underline{B}^i\, \underline{U}^i(T) \tag{1}$$

$$\underline{Y}^{i+1}(T+1) = \underline{C}^i\, \underline{X}^i(T) + \underline{D}^i\, \underline{U}^i(T) \tag{2}$$

For later purposes we will assume $\underline{X}^o(T)=\underline{0}$, $\underline{Y}^o(T)=\underline{0}$ $\underline{X}^P(T)=\underline{0}$, and $\underline{U}^P(T)=\underline{0}$. The values for the matrices $\underline{A}^i$, $\underline{B}^i$, $\underline{C}^i$, and $\underline{D}^i$ are stored in the PARAM's and can be changed by their associated microprocessors to implement a time-varying system if so desired.

III. The Energy Production System Model

The basis for the energy production system model used for this work is the one developed by Maxim and Brazie [3] for analyzing the relationship between an energy system's efficiency and environmental polutants. However, our model will include other societal impacts in addition to environmental polution. In this model the entire energy production system consists of energy chains, each chain representing the processing of an energy resource used to generate energy of a given type. The structure of the model is shown in Fig. 2. A chain represents the processing of a particular resource such as natural gas, coal, or solid wastes from extraction to the point of consumption. Each energy chain consists of a cascade of stages that are necessary for processing the resource, for example extraction, transportation, and storage. At each stage of the processing chain the outputs include energy losses and societal impacts. Inputs to each stage include the resource to be processed and energy inputs from its own and other chains as required.

The jth energy chain consists of a cascade of J_j stages, where in this paper we assume all J_j are equal with J_j=J+1. A typical stage i of the jth chain depicting the stage's inputs and outputs is shown in Fig. 3. By assumption there are a total of G energy chains in the entire energy production system. We let

c_j^i = the amount of energy resource input to the ith stage of the jth chain;

$c_j^{J_j+1} = c_j$ = the amount of energy that is the final output of the jth chain.

The following coefficients are used in this model:

α_j^i = the fraction of the input to the ith stage of the jth chain (c_j^i) which is converted to usable output of this stage (c_j^{i+1}) for input to the next stage.

β_{jk}^i = amount of energy of the kth chain required as input to the ith stage of the jth chain per unit input to the ith stage of the jth chain (c_j^i)

δ_{jk}^i = societal impact of the kth type per unit input to the ith stage of the jth chain (c_j^i).

A measure of the efficienty of the ith stage of the jth chain is given by the following expression:

$$\alpha_j^i c_j^i/(c_j^i + c_j^i \sum_{k=1}^{G} \beta_{jk}^i) = \alpha_j^i/(1+\sum_{k=1}^{G} \beta_{jk}^i) \tag{3}$$

IV. Implementation of the Energy Production System Model with the Multiple Microprocessor Network

The multiple microprocessor network developed in section II can now be used to implement the energy production system model presented in section III Each stage of an energy production chain is implemented with one microprocessor and its associated memories. The same numbered stages of the energy chains use the same memory phases in the MMN with the phases ranging from 0 to P=J+1. The amount of resource to be processed by an energy chain stage is obtained from an INRAM in the phase 0 memories for stage 0 and for the remaining stages from an INTRAM in the phase i memories for stage i. A stage i stores the amount of resource to be processed by the next stage i+1 in an INTRAM in the phase i+1 memories except for the last stage J which stores the amount of energy produced by the energy chain in the phase J+1 memories. The conversion losses, total energy required from all chains, and societal impacts are stored as outputs for each stage i in three

OUTRAM's located in the phase i+1 memories.

The hardware configuration for all but the first or last stages in the energy chains is shown in figure 4. This physical arrangement has the following three busses so that the microprocessor can communicate with its attached memories: 1) bus 1 for the PARAM and phase i memories, 2) bus 2 for the phase i+1 memories, and 3) bus 3 for the ROM. The ROM of each microprocessor has its own bus so that a program instruction can be fetched and decoded without using the buses connected to the memory phases. The INTRAM of phase i and the microprocessor's PARAM are contained in the same physical memory so that parameter values can be entered using bus 1. All three of the OUTRAM's of phase i+1 are also contained in the same physical memory and the results that are stored in them can be extracted from the system using bus 2. These two sets of RAM's are combined in the same physical memory to minimize the amount of hardware needed, as semiconductor memory packages come in sizes that are large enough for the combined memories.

Using these stage building blocks, the entire energy production system can be constructed as shown in Fig. 5. In this structure phase 0 contains only INRAM's and PARAM's for stage 0 of the energy chains and phase J+1 contains only OUTRAM's. Connecting identically numbered phases of each energy chain to the same bus facilitates entering and extracting data as information transfer with all the memories of a phase takes place with a single bus. The system is modular as an additional energy chain can be added by inserting a microprocessor between every stage for that chain with the necessary memories in each memory phase.

Equations (1) and (2) are used to describe the processing performed by the multiple microprocessor energy production system model. Since there are only INRAM's in the first phase, $\underline{X}^0(T)=\underline{0}$, $\underline{Y}^0(T)=\underline{0}$, and $u_k^0(T)=c_k^0(T)$, and since there are only OUTRAM's in the last phase, $\underline{X}^{J+1}(T)=\underline{0}$ and $\underline{U}^{J+1}(T)=\underline{0}$. In all the remaining phases no INRAM's are present so $\underline{U}^i(T)=\underline{0}$ and $x_k^i(T)=c_k^i(T)$ for all these phases. The matrices $\underline{A}^i$, $\underline{B}^i$, $\underline{C}^i$, and $\underline{D}^i$ are described in Appendix I.

After entering the values of the system parameters in all the PARAM's and the amount of raw energy resource to be processed in the phase 0 INRAM's, the network performs the necessary calculations one stage at a time and the results become available for these initial values in consecutive memory phases as the processing proceeds down the network. The computer system requires J processing cycles of length T to complete one simulation. As only one stage of microprocessors is active for one set of initial values at any time, new initial values can be continuously entered in the INRAM's of phase 0 so that the system will use all of its microprocessors all of the time. Results can then be continuously extracted from all the memory phases. In the network a phase i+1 INTRAM is an output location for stage i but an input location for stage i+1. When all microprocessors are active during the processing cycle, different memory locations in an INTRAM will be used for storing and extracting information so that the possibility of a microprocessor altering a location in the INTRAM before it is used as input by another microprocessor is avoided.

All the microprocessors in the network execute the same program that is initiated by an external clock. The program first establishes the INTRAM addresses to be used for extracting and entering data and then performs the necessary calculations and data handling tasks.

V. Conclusions

This paper has presented 1) a multiple microprocessor network that can be used to construct multiple microprocessor systems and 2) a large-scale energy production system model. The network was then used to construct a computer system that simulates the energy system model. The implementation of the energy production model with the multiple microprocessor computer network offers the following advantages:

1) hardware modularity for easy system expansion;
2) the potential for increased processing throughput with multiple processing units;
3) reduced software requirements with identical programs repeated throughout the network.

This energy production system model consisting of multistage energy chains is equivalent to the "input-output model" [3,7,8] used in the modeling of economic systems as shown in Appendix II. Consequently, the results [9,10,11] that have been obtained for "input-output models" can be applied to our multiple microprocessor network model.

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Appendix I

The values for the elements of the matrices $\underline{A}^i, \underline{B}^i, \underline{C}^i$, and $\underline{D}^i$ in equations (1) and (2) required to implement the energy production system with the multiple microprocessor network are the following, all for $1 \le k \le G$: For $1 \le j \le G$

$$a^i_{jk} = \begin{cases} 0 & \text{for } i=0 \\ \left.\begin{cases} \alpha^i_j & \text{if } j=k \\ 0 & \text{if } j \ne k \end{cases}\right\} & \text{for } 1 \le i \le J-1 \\ 0 & \text{for } i=J \end{cases}$$

$$b^i_{jk} = \begin{cases} \left.\begin{cases} \alpha^i_j & \text{if } j=k \\ 0 & \text{if } j \ne k \end{cases}\right\} & \text{for } i=0 \\ 0 & \text{for } 1 \le i \le J \end{cases}$$

For $1 \le j \le 2G+1$

$$c^i_{jk} = \begin{cases} 0 & \text{for } i=0 \\ \left.\begin{cases} 1-\alpha^i_k & \text{if } j=1 \\ \beta^i_{k,j-1} & \text{if } 2 \le j \le G+1 \\ \delta^i_{k,j-(G+1)} & \text{if } G+2 \le j \le 2G+1 \end{cases}\right\} & \text{for } 1 \le i \le J \\ \alpha^J_k & \text{when } j = 2G+2 \text{ (for } i=J) \end{cases}$$

Here the last $\underline{C}^i, i=J$, has an extra row since there is an extra OUTRAM in the last phase of memories to store the final amount of energy generated.

$$d^i_{jk} = \begin{cases} \left.\begin{cases} 1-\alpha^0_k & \text{if } j=1 \\ \beta^0_{k,j-1} & \text{if } 2 \le j \le G+1 \\ \delta^0_{k,j-(G+1)} & \text{if } G+2 \le j \le 2G+1 \end{cases}\right\} & \begin{array}{l} \text{for } i=0 \\ 1 \le j \\ \le 2G+1 \end{array} \\ 0 & \begin{array}{l} \text{for } 1 \le i \le J \\ 1 \le j \le 2G+2 \end{array} \end{cases}$$

Appendix II

The following results show that the energy production system model consisting of multistage energy chains is equivalent to the "input-output model" used in the modeling of economic systems.

ω_{kj} = the total demand for energy from the kth chain required to support energy production in the jth chain

$$= \sum_{i=1}^{J_j} \beta^i_{jk} \epsilon^i_j \qquad (4)$$

$$\epsilon_j = \alpha^{J_j}_j \ldots . \alpha^{i+1}_j \alpha^i_j (\epsilon^i_j)$$

$$= \left(\prod_{\omega=i}^{J_j} \alpha^\omega_j \right) \epsilon^i_j \quad \text{for any } i,\ 1 \le i \le J_j$$

Therefore $\epsilon^i_j = \epsilon_j / \prod_{\omega=i}^{J_j} \alpha^\omega_j$ (5)

Substituting equation (5) into (4):

$$\omega_{kj} = \eta_{kj} \epsilon_j$$

$$\text{where } \eta_{kj} = \sum_{i=1}^{J_j} \beta^i_{jk} / \left(\prod_{\omega=i}^{J_j} \alpha^\omega_j \right) \qquad (6)$$

Each energy chain in the system must provide the demand for its energy both internal as well as external to the energy production system.

$\sum_{j=1}^{G} \omega_{kj}$ = total internal demand for ϵ_k in the energy production system

λ_k = total external demand for ϵ_k outside the energy production system

$$\text{So } \epsilon_k = \sum_{j=1}^{G} \omega_{kj} + \lambda_k$$

$$\epsilon_k = \sum_{j=1}^{G} \eta_{kj} \epsilon_j + \lambda_k \qquad (7)$$

The following matrices can now be defined:

$$\underline{E} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_G \end{bmatrix} \quad \underline{A} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_G \end{bmatrix} \quad \underline{H} = \begin{bmatrix} \eta_{11} & \cdots\cdots & \eta_{1G} \\ \vdots & & \vdots \\ \eta_{G1} & \cdots\cdots & \eta_{GG} \end{bmatrix}$$

Using equation (7), the quantities defined above, and $\underline{I}$ for the identity, we have:

$$\underline{E} = \underline{H}\,\underline{E} + \underline{A}$$
$$(\underline{I} - \underline{H})\,\underline{E} = \underline{A} \tag{8}$$

Equation (8) is the "input-output model" where $\underline{H}$ is the matrix of technical coefficients, $(\underline{I}-\underline{H})$ is the Leontief matrix whose elements are the interdependence coefficients, and $\underline{A}$ is the vector of final demand.

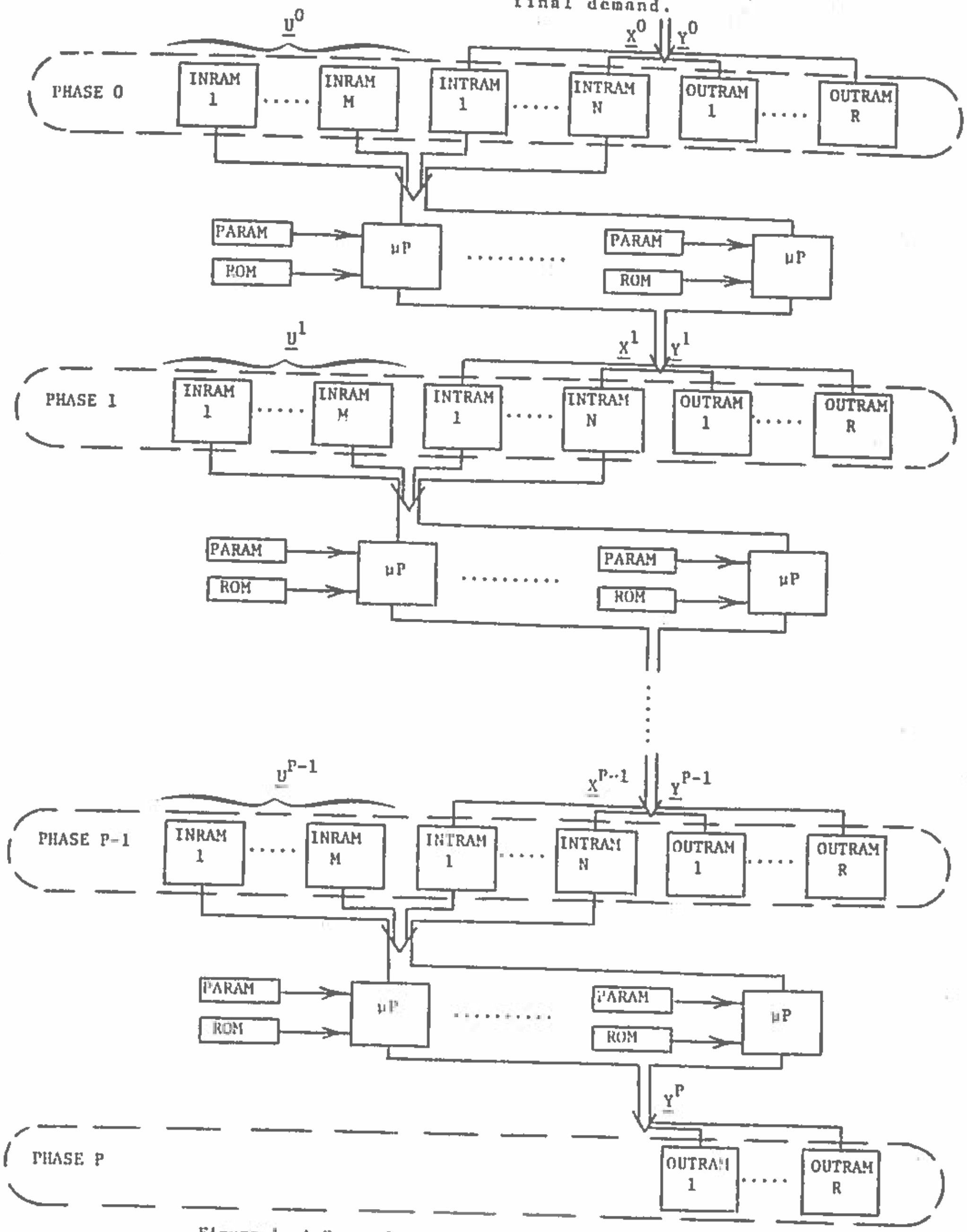

Figure 1. A General Multiple Microprocessor Network

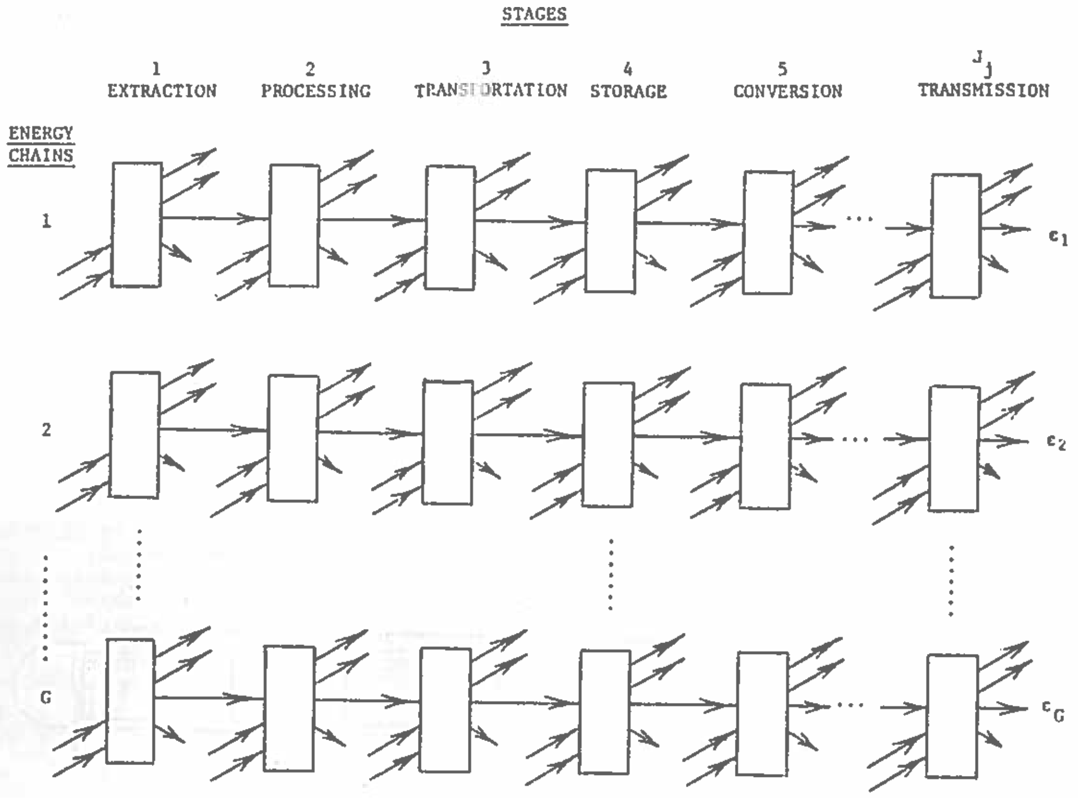

Figure 2. The Energy Production System

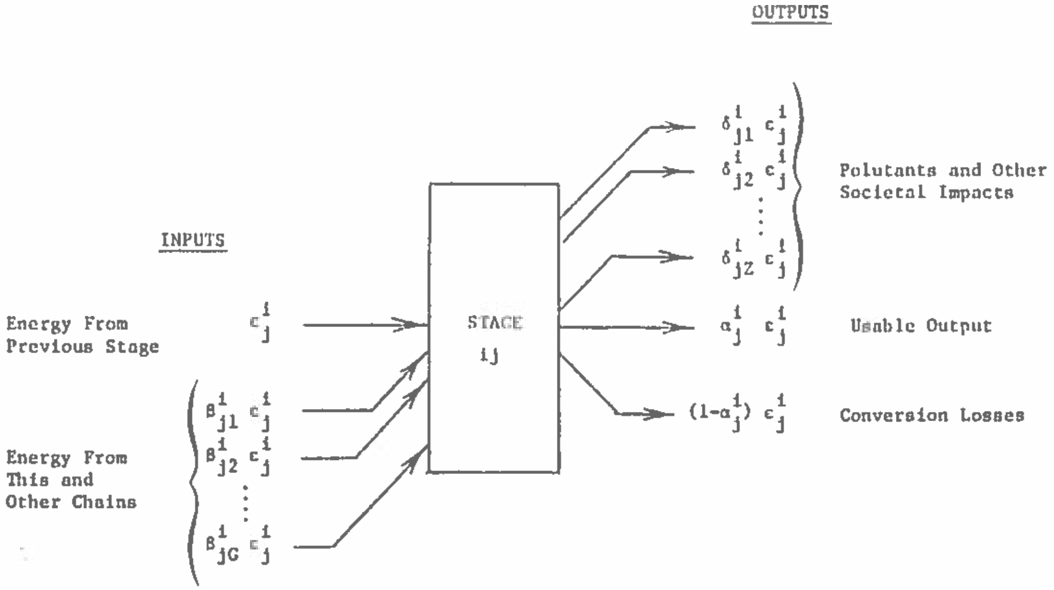

Figure 3. The Inputs and Outputs of One Stage in an Energy Chain

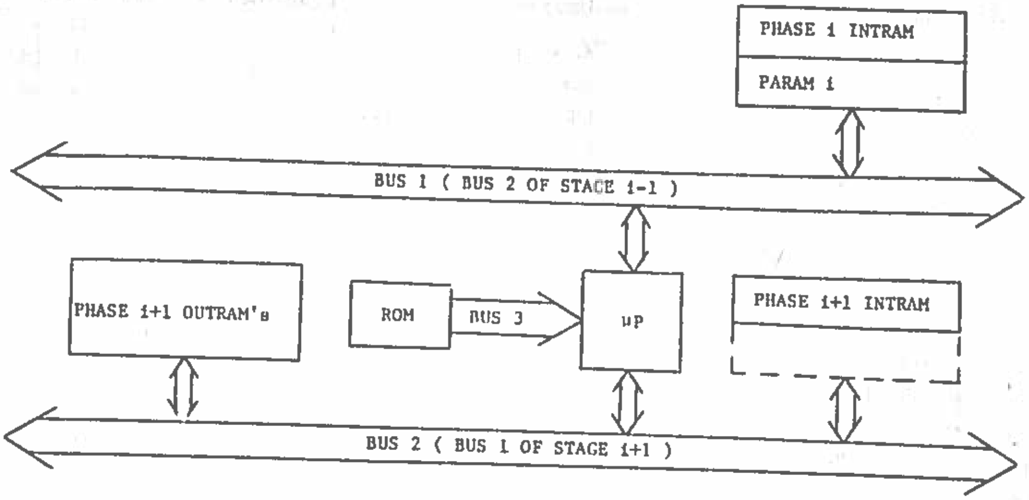

Figure 4. Hardware Configuration For Stage i

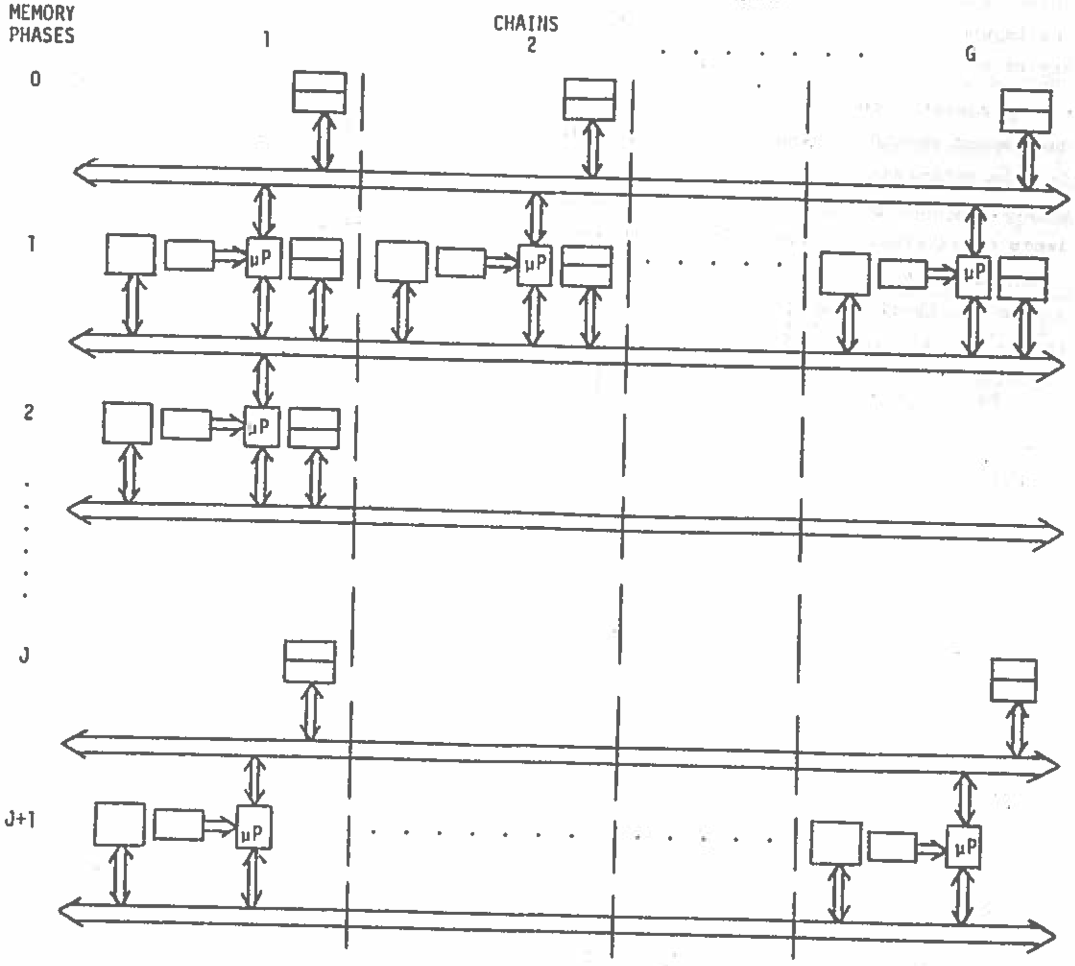

Figure 5. Implementation of Entire Energy Production System

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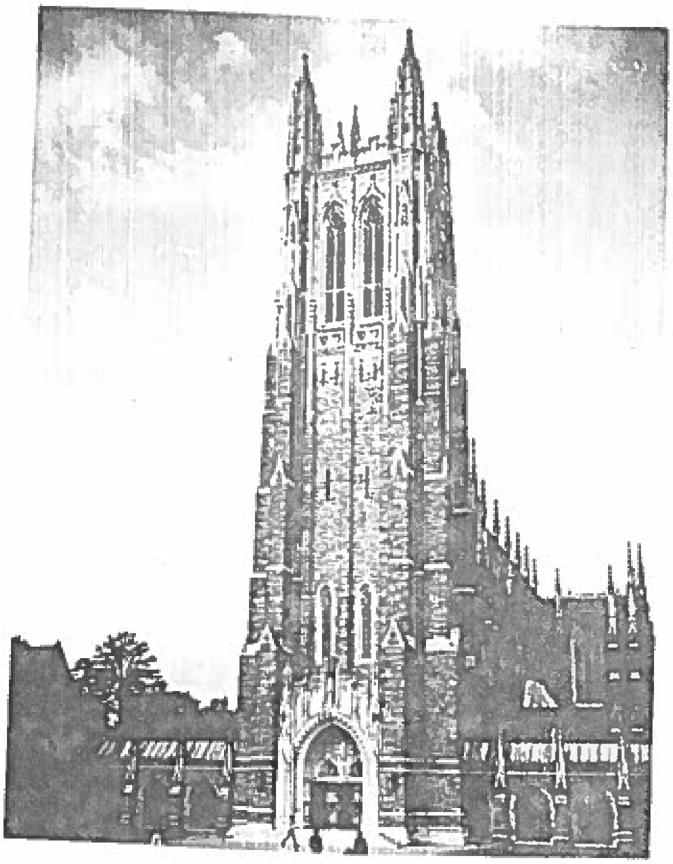

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