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ANL/CTR Technical Memorandum Number

Presented at:

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Introduction

With the rapid progress being made toward scientific demonstration of controlled thermonuclear reactions, much effort and enthusiasm have recently gone into studies related to the engineering and technological feasibility of fusion power, both in the U.S. and abroad. In the U.S., this activity has thus far culminated in a number of conceptual designs based on several different confinement schemes. Similar, but perhaps less diverse or extensive, efforts have been carried out in Western Europe and the Soviet Union.

The major contribution these point designs have made is to identify some important engineering and technological problems associated with a particular confinement concept that must be solved before controlled fusion can become a viable source of commercial power. However, beyond these point designs, a comparison among alternative confinement schemes is required so that decisions relating to alternative R & D funding strategies will be, at the least, made on a self-consistent basis. Furthermore, such comparisons must be based not on the conceptual designs extent in 1975, which are of necessity tentative, but rather on technology and plant economics expected at the time of introduction of fusion power into the economy (circa 2000+).

Clearly the task of estimating power plant performance and economics on an absolute scale, given the present state of the art of fusion reactor design, is formidable if not impossible. One method which lends itself to making self-consistent sets of comparisons, however, is systems analysis. Mathematical models of fusion power plants can be developed to estimate performance using consistent criteria and unit costs for items such as environmental insult, components (i.e., the cost of building superconducting magnets or energy storage systems), interest, profit, escalation, etc.

The objective of the fusion systems analysis at ANL is to develop simulations to compare alternative conceptual designs of magnetically confined fusion power plants. With completed simulations, the need for and influence of technological advancement can be assessed, and decisions on R & D programs will be simplified. For instance, using the simulations, changes in the plant figure of merit (MW output or $/MW-hr) can be estimated that result from an increase in injector efficiency or a reduction in energy storage cost. The sensitivity of the objective function to component performance will act as a guideline for component development. The cost of power production is ultimately the overriding criterion for making comparisons, and emphasis will be placed on accurately computing cost, i.e., the inclusion of the direct as well as the external costs. However, given the present knowledge concerning component performance and cost, the emphasis has been placed on sensitivity studies.

This paper describes the last year's work. The methodology employed and the progress made in implementing this methodology are discussed.

Simulation Development

The keystone of the systems studies being developed at ANL for DCTR is the power plant computer simulation. It is expected that the mathematical modeling will evolve over a period of time into a complex computer code. This will arise due to: 1) a deeper understanding of the physical processes occurring in the subsystems as more complete theoretical and experimental results become available; 2) the inclusion of parameter constraints as they become known; and 3) conceptual changes required to accommodate problem areas as they are revealed by analytical and experimental programs. Thus the methodology initially employed in the development of the computer code is an important factor in the degree of success achieved.

The problem of code-complexity produced a "software crisis" in the computer industry in the late sixties. The industry responded by creating a new discipline, "software engineering." Some of the techniques developed for designing and coding large operating systems and data processing programs should be useful in the engineering simulation field. Specifically the top-down, structured program methodology formally set forth by Dijkstra,[1] Mills,[2] and others has been selected for this work[3] since it has several desirable applications to large-scale engineering systems studies. These are:

1. The approach to the development of the physical model of a system is mirrored by the top-down programming procedure; that is, the top-down construction of the computer code parallels the progressive description of the plant into layers of systems or subsystems with progressively greater detail.
2. The resulting code is highly flexible, and modular programming is facilitated since additional information such as design decisions and improvements in the degree of sophistication is easily included.
3. The programming and debugging begin immediately, and a working model is quickly achieved with simplified functional specification of the lowest level (i.e., "program stub") of the programming pyramid.

The choice of the programming language, PL/I, was based on the ease with which structuring is facilitated. PL/I also allows for the use of many of the existing program modules that have been inherited from the fission era, written in FORTRAN as subprograms.

A considerable amount of time has been spent during the last year in developing higher order executive routines to handle the large amounts of input and output data generated by complex engineering-oriented systems codes. The configuration shown in Fig. 1 provides the structure from which any of the reactor simulations can be executed. The system has provisions for parameter search and optimization procedures as well as for several different display and data storage options. Each capability was added as demanded by immediate project needs. The following considerations, though general, are based on the empirical foundation of the code itself.

Using Dijkstra's notion of "levels of abstraction," each capability was moved up to the highest level which could be found for it. Although the effort started with a theta-pinch simulation, its upper levels contained no elements corresponding to the theta pinch or indeed to any kind of power plant at all. Hence it was natural to write a generalized engineering simulation system for wider use. The system presently consists of three parts: an interactive controller, a batch controller, and an output processor.

Working from the "outside in,"[4] one starts with the user interface. Heavy reliance is placed on TSO (IBM's time sharing option) for program development and debugging and for the batching and maintenance of production programs. Such activities fall into patterns and have been automated by procedures written in TSO command language, JCL, PL/I, and assembler language. These procedures were integrated to form an interactive controller, though the changing needs of the project have prevented it from attaining a fixed form. If the code is batched, interactive control is relinquished, but it may still be required to execute a preplanned sequence of operations, for example, to perform a parameter search or to carry out an optimization, under a control which must of necessity be automatic in the batch environment.

The batch controller is a PL/I main procedure made up of two internal procedures. The first, the control procedure, is at a level of abstraction that contains no identifiers relating to any particular power plant type. It con-

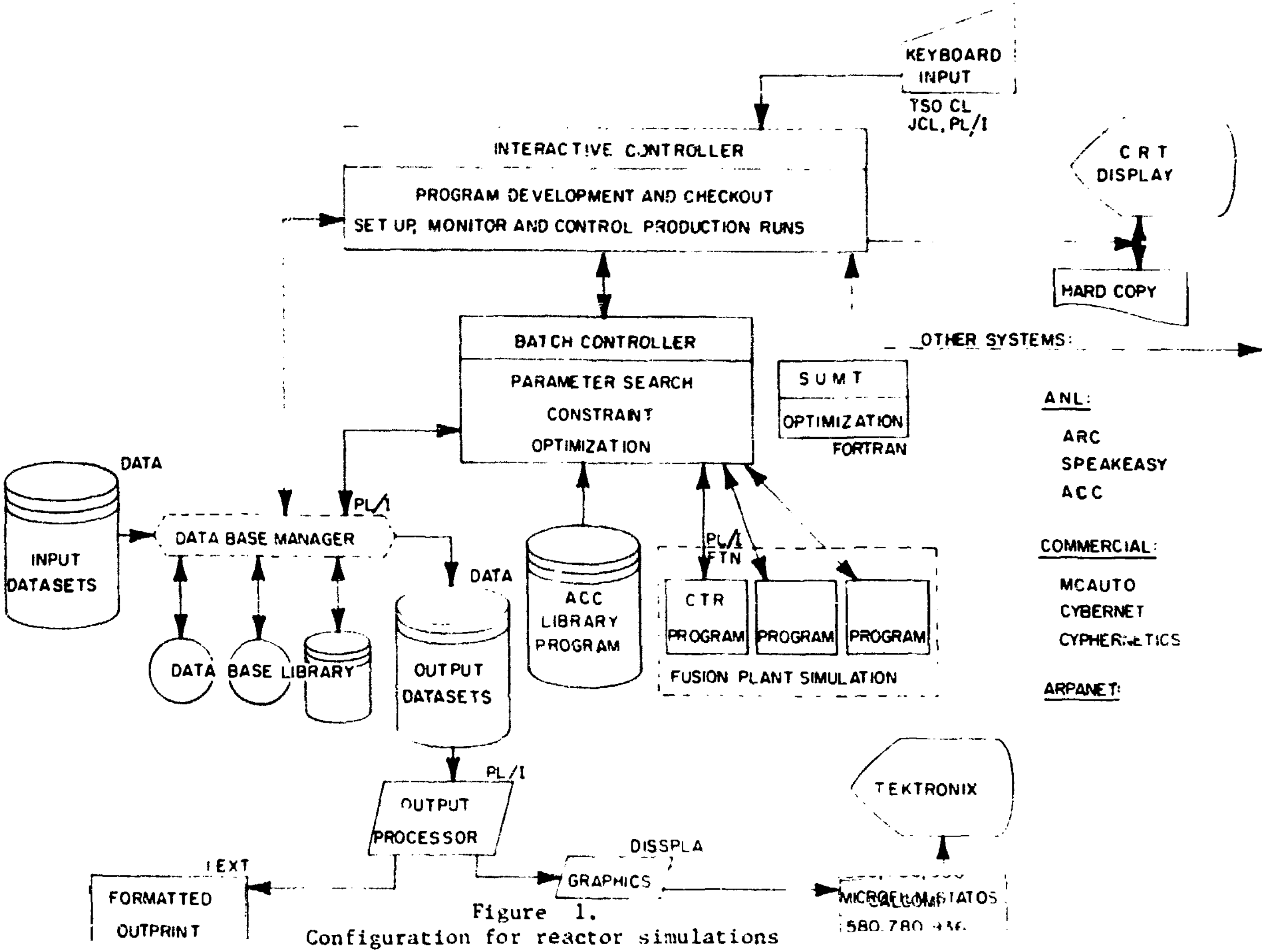


Figure 1.
Configuration for reactor simulations

trols the second, the modeling procedure, where labels and variable names, but not its overall structure, do relate to particular fusion reactor concepts.

Output from a parameter study may be quite voluminous, so it is passed to a disk where parts can be selected for further analysis by the output processor.

A simple optimizer is built into the control procedure. It can be replaced by one of the large, stand-alone optimization programs made available through our close association with Argonne's MINPACK project.[5]

The modeling procedure is arranged in levels corresponding strictly to decomposition levels in the analysis of the power plant: Subprocedures correspond to subsystems. Calls are allowed only down to the next level in such a way that the program tree (structure diagram[6]) is isomorphic to the subsystem decomposition of the plant. The relation "is called by" then corresponds to the relation "is a subsystem of." The two relations induce abstractly identical hierarchies, undisrupted by Go Tos and common blocks, which are prohibited.

This structural identity is to prevent the complexity of the code from compounding the complexity of the power plant. The source listing reflects not only the execution of the modeling procedure but also the structure of the modeled system.

When a branch of the tree reaches a certain stage, it is broken off to form an external procedure, so the level structure does not correspond to the module structure. The main procedure left behind has continued to be larger than permitted by the rules of structured programming;[2] but the revolutionary increase in programming power given by interactive use of the PL/I Checkout Compiler has turned this large size into an asset.

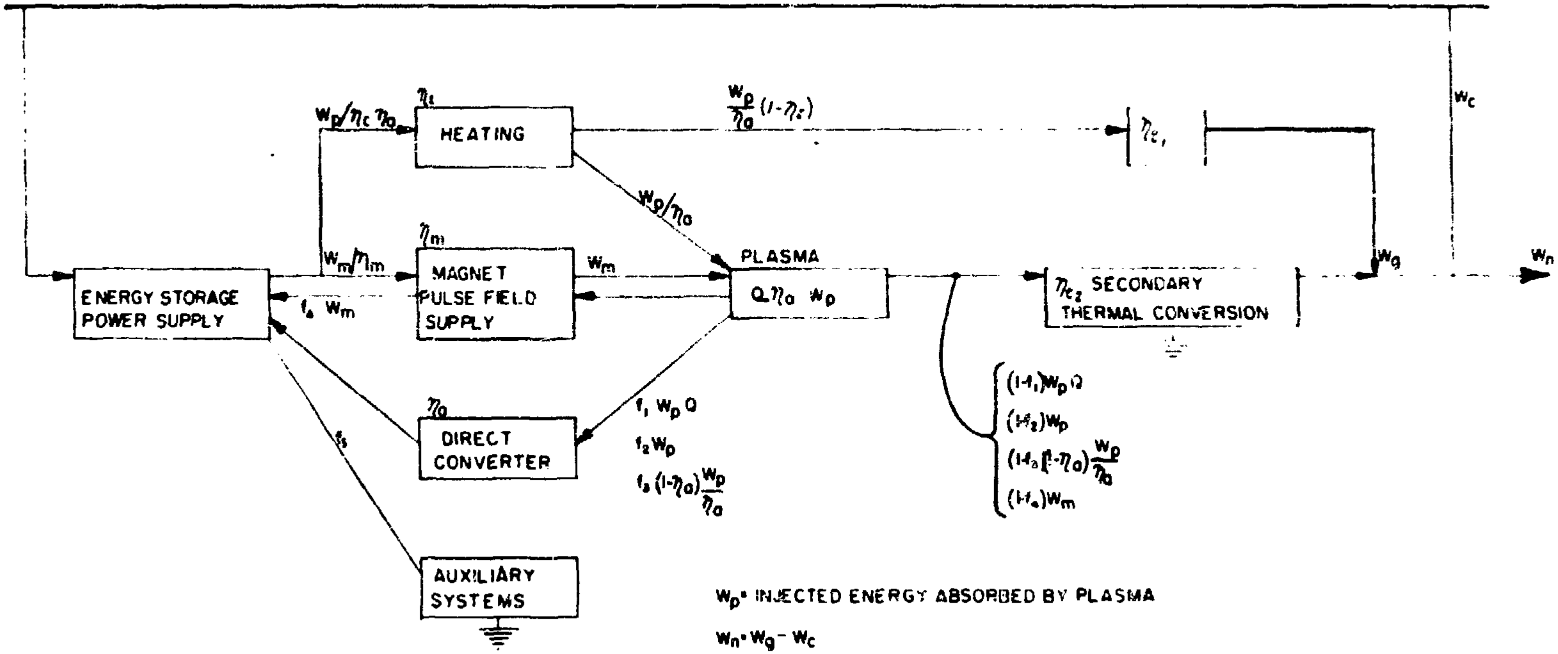
There are other violations of those rules. The plant geometry subprocedure did not fit on the tree; its variables are defined globally, to provide an environment for the entire tree. Nor did the cost subprocedure fit, for which, conversely, the entire tree seems to provide an environment.

Plant Simulation

Systems studies are carried out by developing an equivalent model of the physical system of interest and then studying the behavior of the model. Such a model is composed of two sets of approximate mathematical relations describing the performance of the system components and the inter-relation of the components. Both sets are combined into a computer code that represents the system and can predict its performance.

In a power plant simulation, the natural means for specifying the interrelatio of components is to describe the energy flow. (A second could be to describe the system topology.) Fig. 2 describes the energy flow diagram[7] selected as the conceptual basis for the three classes of fusion power plants, i.e., Tokamak, mirror, and theta pinch. This diagram comprises the six general classes of components in a fusion power plant. They are:

1. Plasma Heating. Proposed methods include adiabatic compression, RF heating, and energetic neutral beam inspection.
2. Energy Supply and Storage. In a steady state mirror reactor, magnetic energy need not be transferred and stored, and the parameters describing these devices will be assigned such that they do not influence the power balance equations. However, both the Tokamak and theta-pinch reactors are transient in nature and, to be economically feasible, require that energy supplied to the pulsed magnetic fields be recovered. Homopolar-type generators are considered adequate in the Tokamak, while faster energy storage systems (capacitors) are also required for the theta pinch.
3. Direct Converters. Some of the charge particles' energy produced by the D-T reaction may be recovered at a higher efficiency than the 30 to 40 percent normally expected from thermal conversion systems. Such devices are being developed, primarily for use with mirror reactors. A reactor could also be conceived producing only charged particles, to produce electricity at high efficiency.



W_p = INJECTED ENERGY ABSORBED BY PLASMA

$W_n = W_g - W_c$

$$W_c + f_4 W_m + \left(f_1 W_p Q + f_2 W_p + f_3 (1-\eta_a)\frac{W_p}{\eta_a}\right)\eta_d = (1+f_5)\left[\frac{W_p}{\eta_s\eta_a} + \frac{W_m}{\eta_m}\right]$$

$$W_n = \left[(1-f_1)W_p Q + (1-f_2)W_p + (1-f_3)(1-\eta_a)\frac{W_p}{\eta_a} + (1-f_4)W_m\right]\eta_{t_2} + \frac{W_p}{\eta_a}(1-\eta_s)\eta_{t_1} + f_4 W_m + \left(f_1 W_p Q + f_2 W_p + f_3(1-\eta_a)\frac{W_p}{\eta_a}\right)\eta_d - (1+f_5)\left[\frac{W_p}{\eta_s\eta_a} + \frac{W_m}{\eta_m}\right]$$

f_1 = PORTION OF ENERGY RECEIVED BY DIRECT CONVERSION – FUSION ENERGY PRODUCED

f_2 = PORTION OF ENERGY RECEIVED BY DIRECT CONVERSION – HEATING ENERGY ABSORBED

f_3 = PORTION OF ENERGY RECEIVED BY DIRECT CONVERSION – HEATING ENERGY SUPPLIED BUT NOT ABSORBED

f_4 = PORTION OF ENERGY RECEIVED BY DIRECT CONVERSION – PULSED MAGNET ENERGY SUPPLIED

f_5 = PORTION OF ENERGY SUPPLIED, CONSUMED BY AUXILIARIES

Figure 2.
Energy flow diagram

4. Fusion Reactor "Core." This consists of the plasma, the first wall, the magnetic shield, and the blanket which surrounds the plasma and converts the neutron kinetic energy into thermal energy. Materials can be incorporated into the blanket design to allow neutron multiplication, thus actually increasing the net energy released per fusion neutrons.
5. Auxiliaries. These include the equipment required to cool the superconducting magnets and pump the coolant and vacuum pumps used to evacuate the plasma chamber.
6. Thermal Converters. The thermal energy contained in the hot primary coolant and other components is converted in a conventional secondary energy converter.

Figure 3 illustrates the information flow throughout the Tokamak simulation. Data describing the plant for which the computation is to be made are obtained from RF DATA. Plasma initial conditions are passed to PLASMA which computes the neutron and electromagnetic wall flux. The neutron wall flux is then used by NEUTRONICS to scale the heat deposition rate in the blanket materials and the electromagnetic radiation is incorporated in the heat load assigned to the first wall. The coolant flow, pressure drop, and approximate size of the coolant passages are computed in the subroutine PRIMARY ENERGY CONVERTER. Conversion of the thermal power removed from the blanket is made in the subroutine SECONDARY ENERGY CONVERTER. The present versions of the fusion power simulation code use a thermal efficiency with an input value of 40 percent. However, an operational code, ENCON, can represent several of the energy conversion options. ENCON uses well-documented lumped parameter representation for each of the components in the secondary side power cycle and iterates through a system of equations to obtain a solution consistent with the heat source data supplied by BLANKET. The information returned by ENCON includes thermodynamic state points in the cycle. This code allows for the options of electrical power

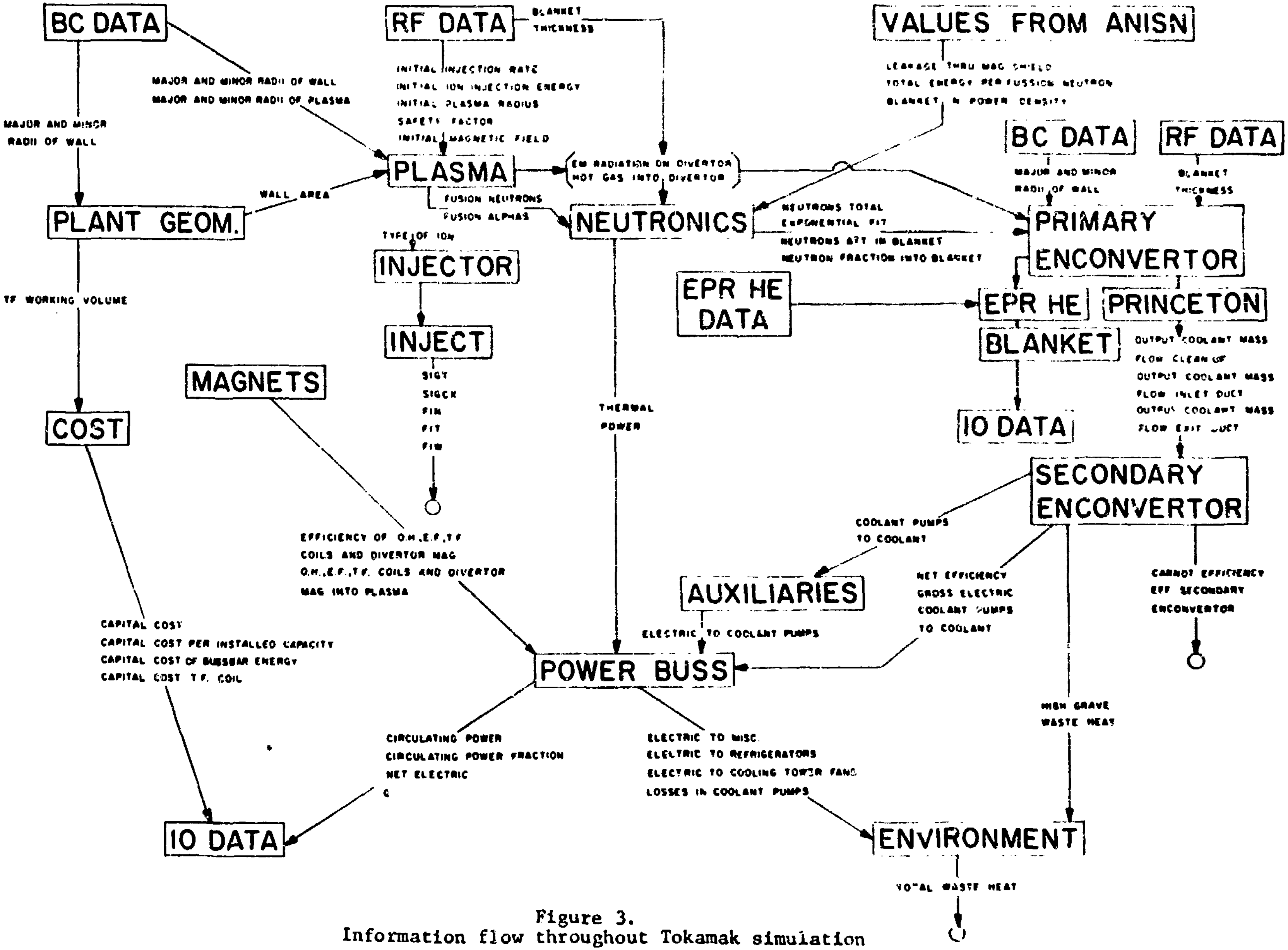


Figure 3.
Information flow throughout Tokamak simulation

production via a gas turbine, two-phase liquid-metal MHD generator, potassium vapor turbine or a steam turbine. ENCON has been used extensively on other studies, and no problems are expected in adapting it to this case.

Theta-Pinch Reactor Simulation

The code which has been developed to simulate the theta-pinch reactor is illustrated in Fig. 4. Detailed discussions of the component subroutines can be found in the Systems Modeling Annual Report.[8] The large codes, such as DTBURN and ANISN, are not directly incorporated into thesystems analysis; however, results from these codes are represented, for a specific range of design conditions, using a generalized interpolation routine.

The theta-pinch simulation has been used extensively, with several interesting results. (See, for example, Ref. 9 and 10.)

Tokamak Reactor Simulation

The Tokamak confinement scheme belongs to the so-called toroidal diffuse pinch family. In this approach, a large axial current is induced in the plasma to provide 1) a pulsed poloidal magnetic field which works together with a steady-state toroidal field to confine the plasma, and 2) initial plasma heating arising from the associated ohmic (joule) heating. External heating of the plasma will be required in addition to the inherent ohmic heating. Proposed methods for the external heating include adiabatic compression of the plasma, radio-frequency wave heating, and energetic neutral beam injection.

In a Tokamak, the pulsed power supply may consist of a superconducting electromagnetic energy storage system as proposed for the theta-pinch reactor. The heating subsystem may be a neutral beam injector or a combination of several schemes. The magnetic induction subsystem corresponds to the primary winding for inducing the axial plasma current. The thermal converter would be the same

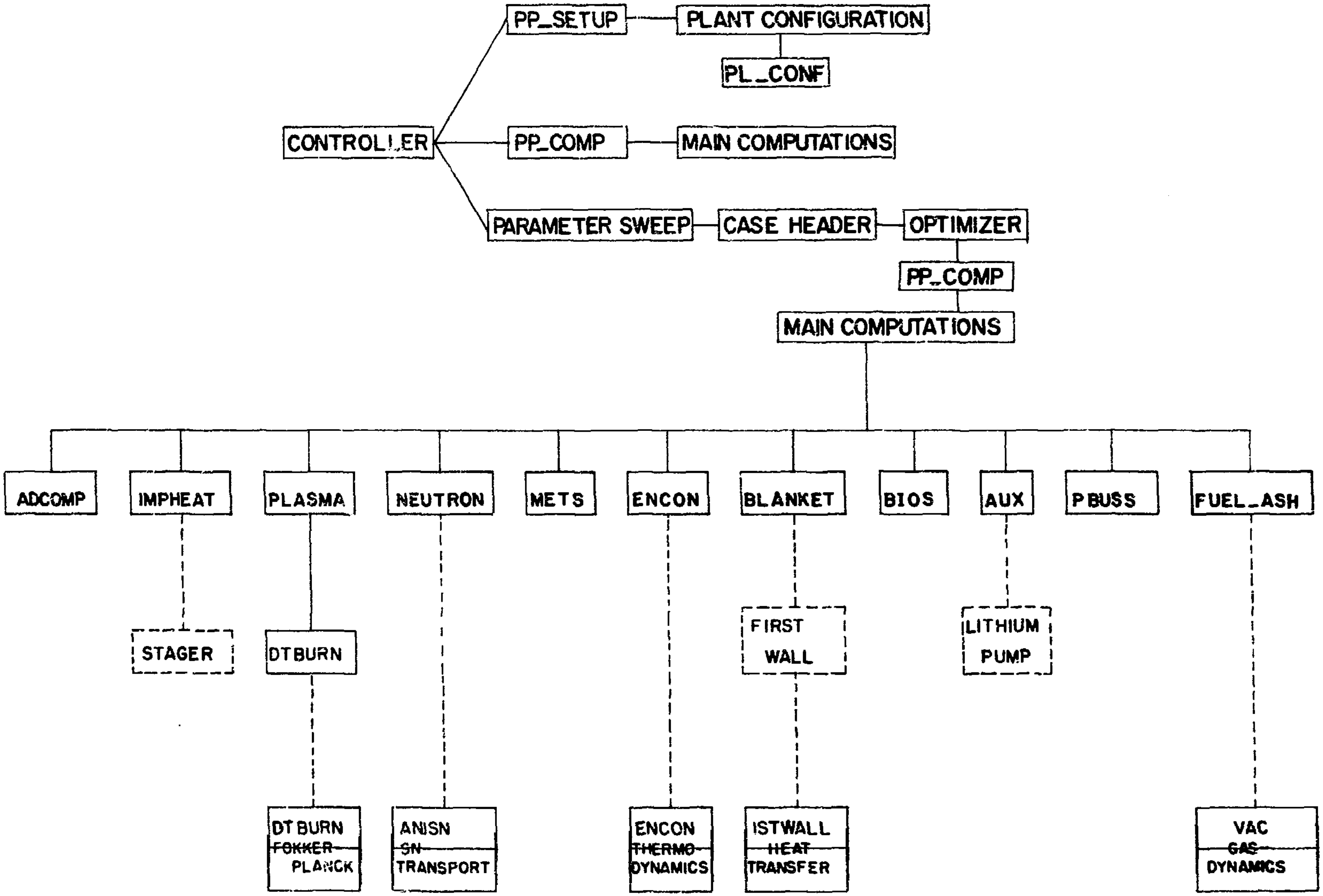

CONTROLLER
PP_SETUP
PLANT CONFIGURATION
PL_CONF
PP_COMP
MAIN COMPUTATIONS
PARAMETER SWEEP
CASE HEADER
OPTIMIZER
PP_COMP
MAIN COMPUTATIONS
ADCOMP
IMPHEAT
PLASMA
NEUTRON
METS
ENCON
BLANKET
BIOS
AUX
PBUSS
FUEL_ASH
STAGER
DTBURN
FIRST WALL
LITHIUM PUMP
DT BURN FOKKER-PLANCK
ANISN SN TRANSPORT
ENCON THERMO-DYNAMICS
ISTWALL HEAT TRANSFER
VAC GAS DYNAMICS

Figure 4.

The following sequence of events is assumed in the operation of the Tokamak reactor.[7] 1) Ionization of the fuel gases and ohmic heating is accomplished by application of the poloidal magnetic field. During this phase the plasma will be heated to several hundred eV. 2) Neutral beam injection will be applied to heat the plasma to the 6 keV ignition temperature. During the heating phase only a fraction, η_a, of the supplied energy (ω_p/η_a) will be deposited in the plasma, and the remaining $(1 - \eta_a)$ portion will appear as heat at the first wall of the reactor. 3) Once the plasma is ignited, alpha-particle heating will cause the plasma temperature to reach its operating (burning) temperature essentially instantaneously. The operating temperature will be ∿15 to 25 keV as determined by the plasma stability conditions. Plasma burning will proceed to the cessation of the pulse. 4) At the end of the pulse, some portion of the plasma energy and the poloidal magnetic energy will be recovered and transferred to the pulsed power supply subsystem by electromagnetic induction.

The present configuration of the Tokamak is illustrated in Fig. 5. The details of the component models are again given in the systems annual report.[4] However, advancements made in the representation of the plasma, magnets, and the primary energy converter should be mentioned. The cost code is essentailly the same procedure used for the theta-pinch simulation with modification to represent Tokamak components.

Rather than use selected data from a Fokker-Planck code, as was done for the theta-pinch simulation, a plasma subroutine incorporating directly the plasma representations of Stacey[11] or Horten[12] was developed. A set of ordinary first order differential equations is solved to predict the time-dependent behavior of the plasma. The model includes the effect of impurities and accounts for the confinement law variations during plasma start up.

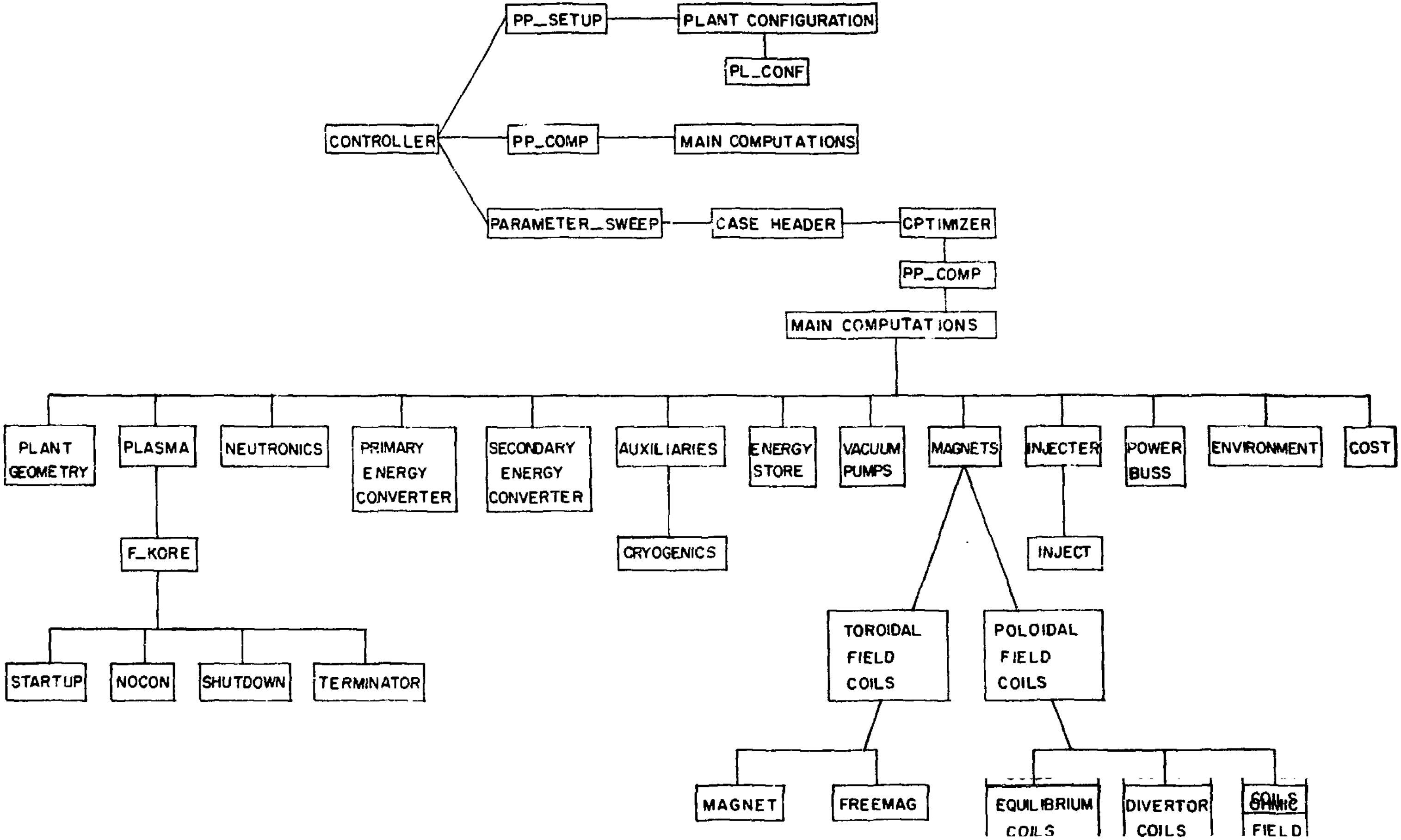


Figure 5.
Present configuration of the Tokamak

Improvements have also been made in the magnet subroutine. The simplified codes developed to represent the theta-pinch magnet system have been replaced with a general finite element code. This code has been modified to represent the behavior of the toroidal field magnets, and work is in progress to represent the ohmic heating and vertical field coils. Ultimately, the entire magnet system will be represented by a single code to account for the interactions between coils during the burn pulse.

Data obtained directly from ANISN for the specific design under consideration are modified in the subroutine NEUTRONICS, using as a scale factor the first wall neutron flux computed by PLASMA. If the blanket dimensions are changed without changing the arrangement of materials within the blanket, the energy deposition is modified using a two component exponential fit to the basic data keeping the total amount of energy deposited a constant. This approximation is valid since 99 percent of the energy is deposited in the first 30 cm of the blanket. However, if the materials are different or arranged differently, a new set of ANISN computations is required.

The first results from the Tokamak simulation are presented in Figs. 6-7. The preliminary results of Fig. 6 show the influence of burn time on net power for an experimental Tokamak power reactor at different field strengths. The importance of long burn time is apparent and may be a strong argument for the inclusion of a divertor. The equilibrium conditions, at the different fields, are at approximately the same ion density. As a result the neutron wall flux was not substantially different for two cases presented.

Figure 7 indicates how the cost of power production is influenced by the magnitude of the net power produced (size of the reactor). The numbers placed on the ordinate of the curve represent a preliminary cost estimate in which the quantities involved in the cost computation have been modified to include the

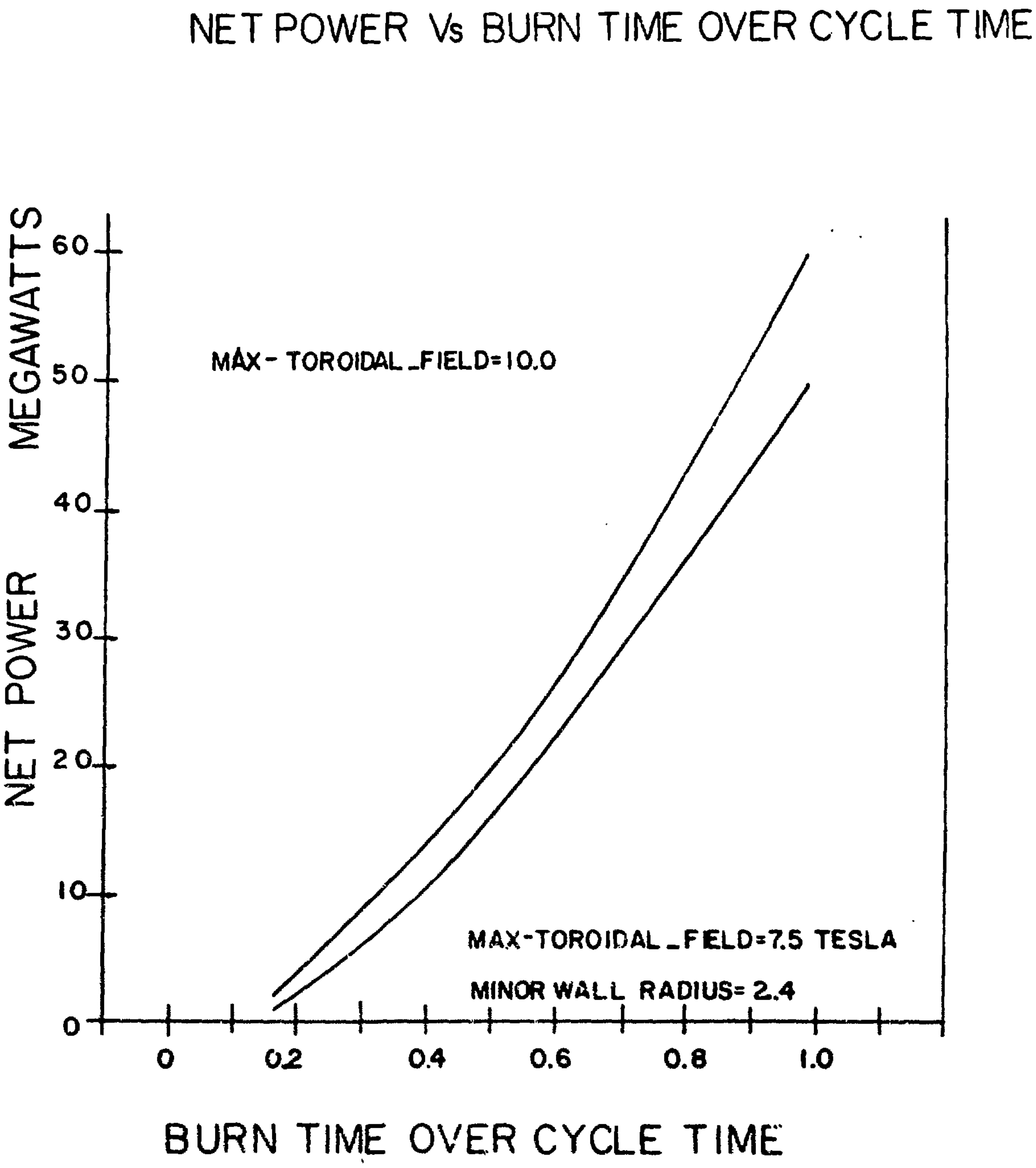


Figure 6.
Influence of burn time on net power for
experimental Tokamak

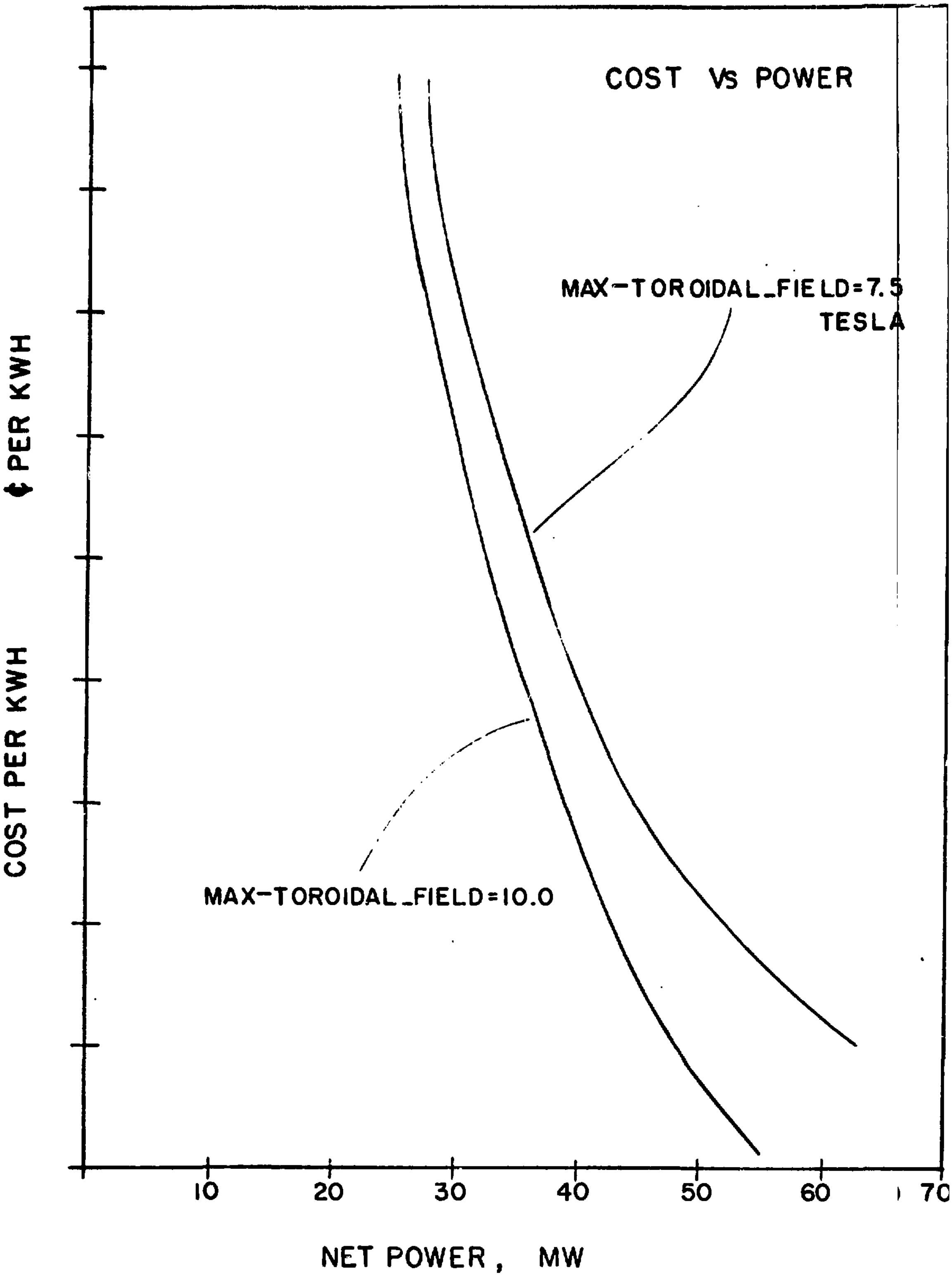


Figure 7.
Effect of net power on cost of power production

time required to carry out remote maintenance, and interest charges necessary to amortize capital expenditures. Not included are the fuel costs and externalities such as environmental impact.

Conclusions

Substantial progress has been made in the development of computer simulations for fusion power reactors. Improvement and updating of the Tokamak and theta-pinch simulations are continuing, and work soon will be initiated on developing a model of the mirror confinement system.

Acknowledgments

This paper includes the work of C. Dennis, S. Grammel, and H. Domanus of Argonne National Laboratory and J. Butler of Butler Associates.

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