7. REACTOR ENGINEERING

S. L. Thomson, A. E. Dabiri, and D. C. Lousteau

CONTENTS

7. REACTOR ENGINEERING

7.1. MAINTENANCE APPROACH

The primary objective of increasing the power density of a fusion reactor is to decrease the size (i.e., volume, mass) of the fusion power core (FPC), which in turn will decrease capital cost, development cost and lead to reduced installation and maintenance costs (i.e., reduced repair and down times and increased capacity factor). This overall approach is expected to reduce the cost of electricity (COE) and to reduce the time and cost required to develop fusion as a commercial power source [1].

Parametric studies show that the minimum COE for the RFP occurs at a power density corresponding to a neutron wall loading in the range 15-20 MW/m^2. The TITAN study elected to develop designs at this point, even though the systems studies predict that the COE increase in going from 20 to 10 MW/m^2 is minor (about 10-15%). One reason for the selection of the absolute minimum COE high neutron-wall-loading design point in the scoping phase is to determine quantitatively the engineering limits to power density for specific integrated designs. A second reason is that there are many issues relating to plant availability that may show a significant advantage for the high-power-density option. Specifically, single-piece FPC maintenance of a totally operational and pre-checked FPC may be possible above a power-density or below a total FPC mass threshold. The power density corresponding to the minimum COE may shift once these issues are quantified into a more elaborate availability model than used so far. Separate availability models are required for the single-piece, or "block", maintenance approach and for the multiple module replacement approach. The TITAN study will quantify the maintenance times in the conceptual design phase by the development of a design that allows single-piece maintenance of the FPC. The advantages of single-piece maintenance will be contrasted quantitatively with the problems of high neutron-wall-loading designs.

Single-piece maintenance of the FPC is expected to reduce maintenance time and risk, and to increase reliability relative to the modular approach. The time-reduction estimate is based on the elimination of component fit-up and sealing in an activated assembly. These operations can be performed on the replacement FPC in the shop prior to FPC replacement while the plant is at power. The financial risk associated with remote operations is also reduced with the single-piece approach. Complex maintenance procedures can result in extended outages, particularly if FPC parts have been deformed, while the single-piece approach establishes a limit on the time required to recover from any failure; a shorter time is required to replace an expended FPC in toto with one that has undergone full non-nuclear testing in conditions that can be more severe than those encountered in actual nuclear service. Reliability improvement is achieved by the complete assembly and testing of the FPC prior to installation. The combined improvements in reliability and maintainability can result in improved plant availability.

The availability of the power plant is determined by the planned and unplanned outages of the reactor and the balance of plant. Typical planned outages for existing large plants are on the order of 40 days/year for coal plants, and up to 60 days/year for nuclear plants. Scheduled maintenance for the balance of plant alone is estimated to require an annual shut-down of 25 days. Typical unplanned outage periods are 50-60 days/year for existing U.S. large plants and this value is also adopted by fusion reactor studies [2], with the majority of the forced outages caused by the reactor (or coal plant boiler) components. For the purpose of the RFP reactor systems model, a typical plant with an aggressive availability goal is assumed to require $\tau_s = 40$ days/event for planned maintenance and $\tau_u = 60$ days per year for forced outages, resulting in an overall availability of 73% for one planned maintenance event per year. As discussed in Sec. 5.2.2, the TITAN studies couple the scheduled maintenance period per event to the neutron wall loading I_w(MW/m^2) and the first wall/blanket fluence lifetime, $I_w\tau$(MWyr/m^2) to give

$$p_f = \frac{\tau_u}{365\left[1+\left(\frac{\tau_s}{365}\right)\left(\frac{I_w}{I_w\tau}\right)\right]} \qquad (7.1.-1)$$

A major goal of the TITAN study is to quantify the expected availability advantage of the compact reactor approach using single-piece maintenance. There is considerable leverage in designing a fusion system that can be maintained in an annual shutdown of 25 days, and this goal appears credible for single-piece maintenance [3]. The unscheduled maintenance time reduction expected because of pre-testing of the FPC and the upper limit on single failure downtime cannot be quantified without the development of an integrated design and equipment specification. If a reduction from 60 to 40 days were achievable, corresponding to a scheduled outage reduction from 40 to 25 days, then the availability would increase from 73% to 82%. A reduction in COE of approximately 10% results and is a major motivation for further development of the single-piece maintenance approach.

Single-piece maintenance requires that the size and mass of the replaceable unit allow routine transport within the reactor cell and maintenance areas. The heaviest single piece considered in conceptual tokamak designs is the TF coil, and reactor cell crane capacities of 600 tonne are specified by STARFIRE and INTOR. This capacity is several times that of standard cranes, but the larger cranes can be supplied at a cost of about 5 M$. An upper limit on crane capacity will be determined by economic trade studies, considering the building space and structural requirements, as well as the crane cost. The trade studies must also consider special horizontal transporters for the heavier components; lifts on the order of 1000 tonnes can be performed with gantry cranes. For guidance during the scoping study phase, the mass at which single-piece maintenance may become unattractive is anticipated to occur at ~500 tonnes.

Transportation of the complete FPC from the factory to the power plant was also considered. The diameter of the FPC is greater than 11 m, which limits the transportation method to barging and special overland transporters. Although special transportation is possible, with limits on plant site selection, the reference approach assumes that the final assembly and testing of the FPC will be performed at the plant site.

A general plant arrangement was developed (Figures 7.1.-1 and 7.1.-2) that takes advantage of the simplicity of the single-piece maintenance approach. A central reactor building containing an enclosed reactor cell connects the shop area at one end to the hot cells and waste processing areas at the other. A straight-through process is envisioned for the FPC replacement, in which the expended FPC is taken to the hot cell for disassembly, and the complete new FPC is brought in from the shop. The intent is to minimize the operations that require the re-assembly of activated or contaminated parts. This approach will simplify the remote maintenance equipment, since the only operation required in the reactor cell is external connections.

7.2. CONFIGURATION DEVELOPMENT

The TITAN study scoping phase considered a broad range of blanket and coolant options, rather than aiming at a complete integrated design. The

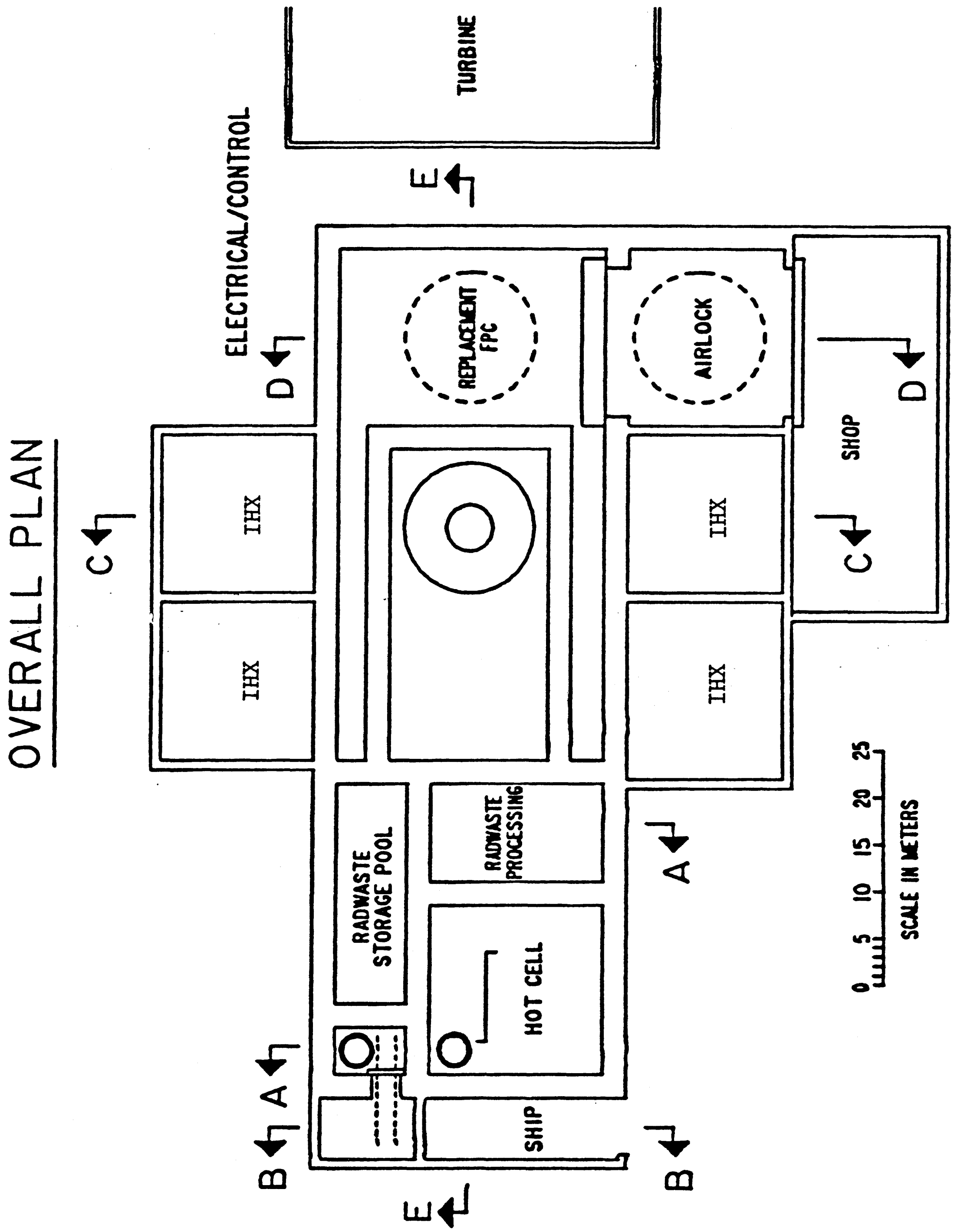

Fig. 7.1.-1. General Plant Arrangement of TITAN.

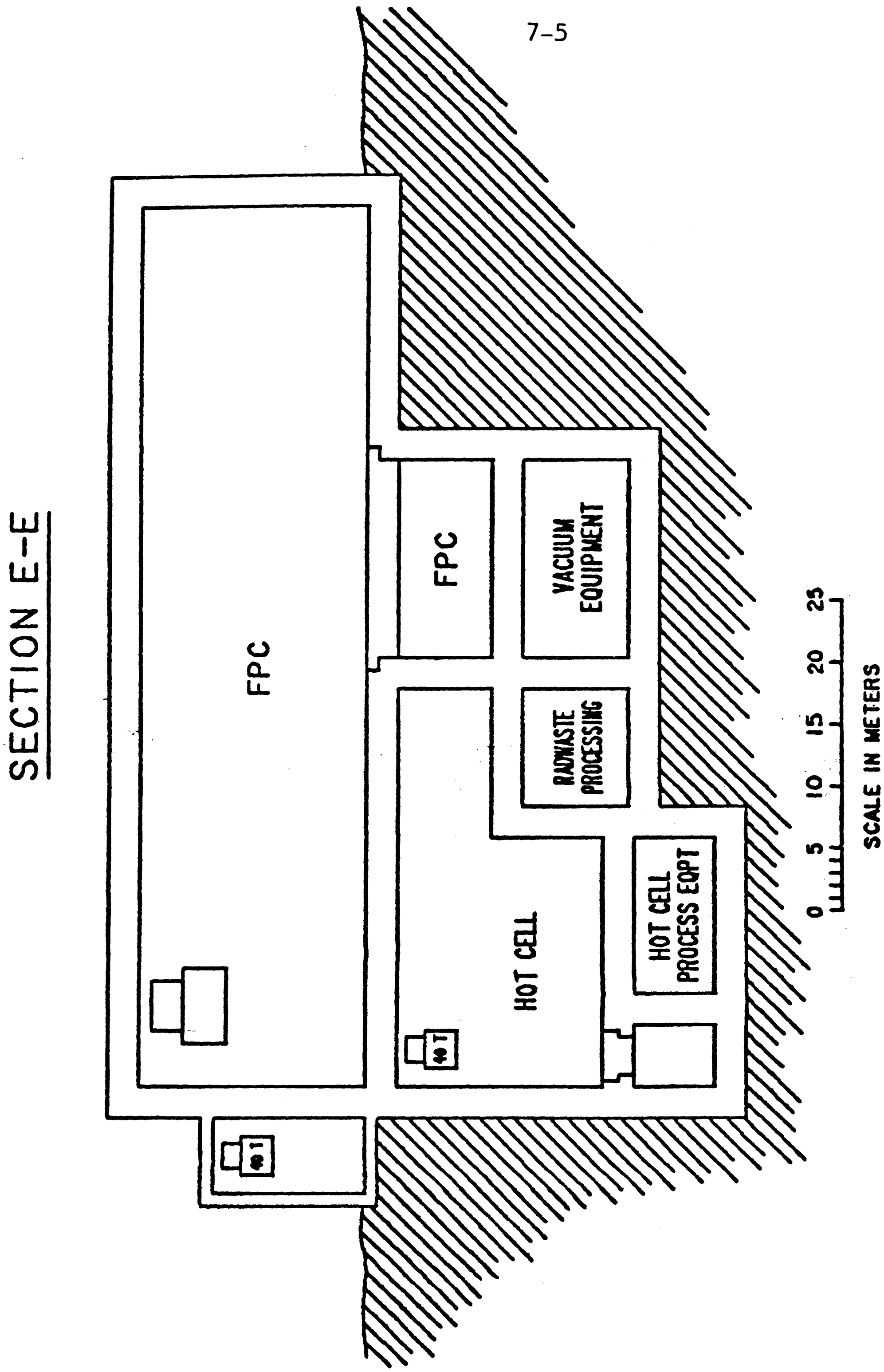

Fig. 7.1.-2. TITAN Reactor Building Elevation.

general issues of the definition of the fusion power core compatible with the maintenance approach and the PF coil structural design were addressed during this phase.

The FPC includes the first wall, divertor (or limiter),blanket, shield, TF and PF coils, and the integral structure. The PF coils of the RFP are massive, are designed for the life of the plant, and are not connected to the rest of the FPC, so they are not considered to be a part of the replaceable FPC. The TITAN study has considered configurations using a completely open PF-coil set, but has not yet found a set that meets the electromagnetic requirements and allows direct torus removal. Therefore, some of the PF coils must be removed or relocated before the replaceable FPC can be removed.

In the compact RFP reactor (CRFPR) design study [3], the replaceable FPC weight (first wall, blanket, shield and TFCs, but not PFCs) is 300 tonnes and it is removed as a unit. The blanket breeder and coolant is PbLi, and most of the drained mass is accounted for by the shield and TF coils, which are reusable. Separate removal of the shield and TF coils in the reactor cell was considered in the scoping phase of the TITAN study (Fig. 7.2.-1) to avoid hot-cell operations to recover and re-assemble these components on a new blanket. This approach would require simple attachments, such as TF coil joints, to limit the downtime. The cost of the TF coils and shield is comparable to the cost of the blanket, and is low enough that re-use of these components may not be justified if complex removal operations are required. The specification of the replaceable FPC components will be investigated further when the integrated design of the reference TITAN blanket, shield and TF coil is completed. In addition, while the long-term radioactivity generated per unit electrical energy is invariant to the FPC (i.e., first wall, blanket, shield, and TFC) replacement schedule, the concentration of the rad-waste depends on replacement schedule, and class C burial considerations may dictate more frequent replacement of these components than is required by damage considerations alone.

The PbLi blanket used in CRFPR, which is unique in its large drainable mass, was not selected as an option in the TITAN scoping phase. The preliminary shield specified for the lithium blanket option, drained of coolant, weighs about 400 tonnes more than that of the drained shield in the PbLi design. The total removable FPC mass is greater than 600 tonnes, so that separation of at least part of the shield from the rest of the FPC may be preferred to single-piece removal. For designs with a lower wall loading, the FPC weight can become so large (e.g., FPC weights over 1000 tonnes for 10 MW/m^2 case) that partitioning of the shield must be considered. The split-shield design would be simplified if the integrated-blanket-coil (IBC) concept [4] is used, so that separate TF coils do not need to be removed to gain access to the shield. Detailed design of the service connections and of the structural supports will be required to determine whether the advantages of single-piece maintenance can be retained with a split-shield design. Further system studies on the blanket and shield design, which give credit to low mass designs, are also warranted. Because of the large mass of the FPC, single-piece maintenance that includes the more massive shield may not be selected for the TITAN reference design. However, the design of the first wall and blanket as a continuous toroidal structure, which is replaceable as a unit, remains a strong possiblity. This will retain the ability to assemble and test fully the FPC subsystems such as the primary coolant channels before installation.

The structural support of the TITAN reference PF coil set was investigated to determine the access to the replaceable FPC. The forces on the coils were calculated for cases with and without plasma current. The maximum force is on the superconducting EF coils and is carried by columns between the upper and lower coils. The structural arrangement has not been optimized pending better definition of the design and of the maintenance procedures for the FPC.

7.3. ENERGY CONVERSION SYSTEMS

A wide range of reactor coolant fluids and conditions were considered during the scoping phase of the TITAN study [5]. The cycles listed in Table 7.3.-I were reviewed for possible application to the TITAN requirements of high power density and efficiency.

Analysis of the energy-conversion system was later focused on the lithium and aqueous blanket designs, for which Rankine steam cycles were selected. This cycle is considered to be the best thermal cycle for source temperatures up to 600°C, which is the upper limit for the lithium coolant in the blanket. The superheated steam cycle was used for the lithium design, while a saturated steam cycle was used for the aqueous breeder design, because of its lower blanket temperature of 320°C.

The PRESTO computer code [6] was used to calculate the power plant thermal efficiencies for various superheat levels. An intermediate heat exchanger and intermediate coolant are specified, with a total temperature difference of 60°C across the heat exchangers. The calculated efficiencies without reheat are

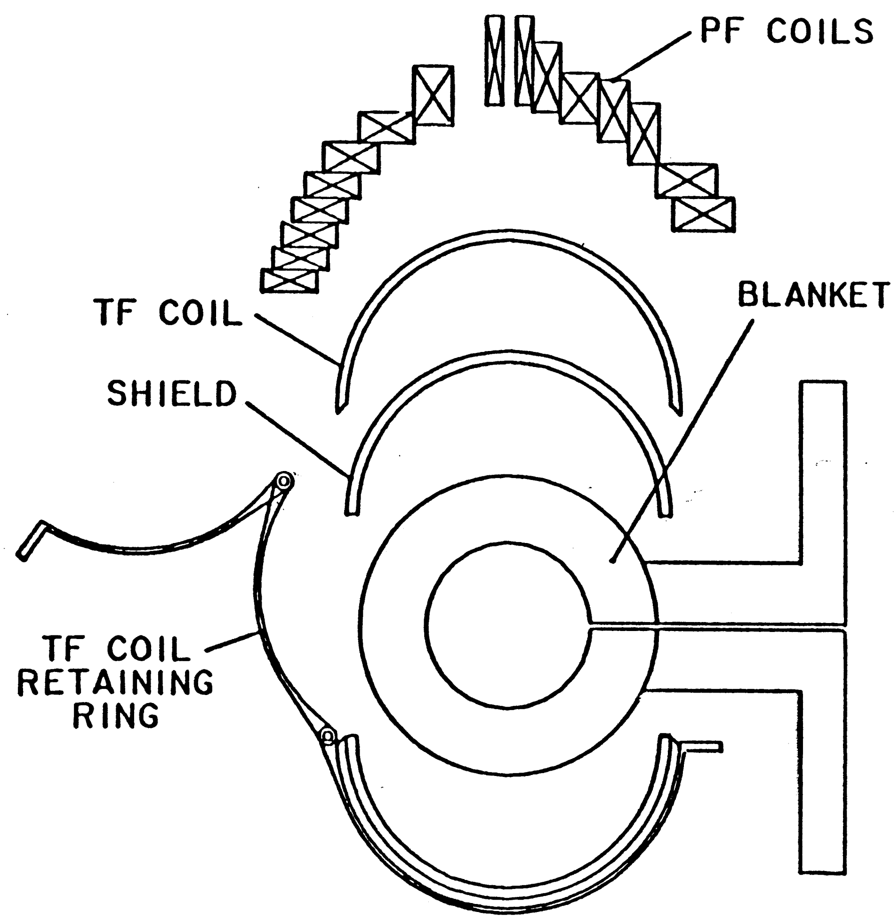

Fig. 7.2.-1. Shield and TF Coil Removal.

TABLE 7.3.-I

Power Cycles Considered for TITAN.

Rankine

- Single (steam, organic, Kalina)
- Supercritical (SO_2, CO_2, H_2O)
- Binary (mercury, potassium, cesium)

Brayton (closed cycle gas turbine, dissociating gas cycle)

Rankine/Brayton

- Field cycle

Combined Cycle

- Brayton/Rankine (gas turbine-steam/organic)

Radiation-Catalyzed MHD

41.0% at a blanket outlet temperature of 600°C and 38.4% at 500°C. Reheat would increase these efficiencies by about 2 percentage points. Higher plant efficiencies are possible by employing a supercritical steam cycle. For example, with a 24 MPa steam pressure and 538°C peak cycle temperature, the efficiency could reach 43%. This plant would use seven feedwater heating systems, with a final feed water temperature of 250°C, and one reheat process. Pinch-point considerations for this cycle forces the inlet liquid lithium temperature to the blanket to be about 350°C. The final decision as to which cycle should be utilized depends on which power plant minimizes the COE, which trades off the increased efficiency with the cost of equipment needed to achieve reheat conditions.

The ORCENT computer code [7] was used to calculate the plant thermal efficiency of the saturated cycle for the aqueous breeder case. The outlet temperature and pressure of the blanket are estimated to be 320°C and 15 MPa, respectively. The plant thermal efficiency is estimated to be about 34.5%, assuming a double-wall heat exchanger with a 40°C temperature drop. This efficiency corresponds to a cycle with a moisture separator and without reheat.

An alternative approach was proposed to cool the divertor of the lithium design with pressurized helium if the heat flux on the divertor plate is more than the heat-removal capability with liquid lithium coolant. A study has been initiated (Sec. 6.5.3) to investigate the heat removal capability of pressurized helium, and to determine the maximum possible exit temperature of the helium coolant for various divertor plate materials. This helium would be used for feed water heating if the temperature were too low for energy conversion.

REFERENCES

1. R. A. Krakowski, R. L. Miller, and R. L. Hagenson, "Prospects for Improved Fusion Reactors," Fourth European Nuclear Conference (ENC-86), (June 1 - 6, 1986). Also LA-UR-86-641.

2. C. C. Baker, M. A. Abdou, R. M. Arons, A. E. Bolon, C. D. Boley, J. N. Brooks, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory Report ANL/FPP-80-1 (September 1980).

3. C. Copenhaver, R. A. Krakowski, N. M. Schnurr, R. L. Miller, C. G. Bathke, R. L. Hagenson, et al., "Compact Reversed-Field Pinch Reactors (CRFPR): Fusion-Power-Core Integration Study," Los Alamos National Laboratory Report LA-10500-MS (August 1985).

4. D. steiner, R. C. Block, and B. K. Malaviya, "The Integrated-Blanket-Coil Concept Applied to the Poloidal Field and Blanket Systems of a Tokamak Reactor," Fusion Tech. 7 (1985) 66.

5. A. E. Dabiri, "Review of the Energy Conversion Systems for the Reversed Field Pinch Reactor", Oak Ridge National Laboratory Report, to be published.

6. L. C. Fuller and T. K. Stovall, "User's Manual for PRESTO", Oak Ridge National Laboratory Report, ORNL-5547, June 1979.

7. L. C. Fuller, "User's Instructions for ORCENT II", Oak Ridge National Laboratory Report, ORNL/TM-6525, February 1979.