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PERFORMANCE PARAMETERS FOR FUSION-FISSION POWER SYSTEMS

D. J. Bender

MASTER

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1. SUMMARY

A comparatively near-term application of present-day fusion research, the hybrid (or fusion-fission) reactor, has recently received increased attention because of its potential to serve as a supplier of fuel to the nuclear power industry. (1,2,3) Because the hybrid produces a source of neutrons external to the fission process, it is a highly flexible nuclear breeding option which permits the use of a wide variety of nuclear fuel cycles.

As a result of the diverse nature of the hybrid reactor, a number of general performance parameters are proposed which will permit comparison of various hybrid reactor configurations. In addition, the relationships developed are used to show that scientific feasibility or "break-even" for the hybrid reactor is near at hand in the fusion program and that attractive commercial reactors can be based on near-term plasma physics.

2. NUCLEAR POWER

There is currently a great deal of world-wide concern regarding the use of the U/Pu fuel cycle (with associated reprocessing) for present fission reactors and eventually the Liquid Metal Fast Breeder Reactor. The concern centers on the existence of large quantities of Pu present in some stages of the fuel cycle and the potential for nuclear weapons proliferation as a result of the availability of this fissile material. Motivated by these considerations, there is presently an intensive effort underway to evaluate, and possibly adopt, alternate fuel cycles⁽⁴⁾ which are characterized by a significantly reduced proliferation risk.

One of the more unfortunate side-effects of the prospect of the abandonment of the U/Pu fuel cycle is that it is contributing to the reluctance of the utility industry to order nuclear plants. This situation is understandable, in that utilities must plan additions to generating capacity with a long-lead time and cannot tolerate the uncertainty of constructing a large, potentially unusable plant. Thus, the

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"nuclear option" or the U.S. energy program is, in reality, non-existent or, at best, very limited in its ability to meet growing energy demand in an energy-scarce future. An expeditious and attractive solution to the fuel cycle problem would contribute to the restoration of nuclear power as a cornerstone of our future energy supplies.

The alternate fuel cycles under consideration⁽⁴⁾ will, almost universally, incur economic penalties as compared to the (Purex) reprocessing U/Pu fuel cycle, or in some instances, may be totally unusable. This situation occurs because the alternate fuel cycles primarily propose incorporating nuclear poisons, in various forms, in the fuel. As fission reactors are inherently neutron poor, they can ill-afford the presence of these strongly neutron-absorbing materials. The key component to successful implementation of the alternate fuel cycles is an external neutron source. Fusion, embodied in the hybrid reactor, could provide this source of neutrons.

3. THE HYBRID OPTIONS

The hybrid is a deuterium-tritium (D-T) fueled fusion reactor which is characterized by the presence of heavy elements in its blanket. It has been a topic of interest to fusion engineers since the advent of fusion reactor design a decade ago.⁽⁵⁾ Basically, three types of hybrid reactor configurations have emerged from this research.

- a. A reactor designed for power production which uses a high blanket energy multiplication, M . M is the ratio of the thermal energy generated on the blanket divided by the energy of the 14.1 MeV fusion neutrons entering the blanket. Typically, these reactors are characterized by $M \geq 25$, which is achieved with the use of fertile and fissile materials in the (subcritical) blanket. The objective of this reactor configuration is to compensate for low plasma power amplification, Q_p , which is the ratio of the fusion power generated divided by the power required to heat the plasma.
- b. A reactor designed for fissile fuel production which incorporates fertile elements in the blanket. Excess neutrons, produced as a result of fast fission of the fertile elements by the fusion neutrons, are captured by fertile nuclei to create fissile nuclei. These blankets also exhibit significant energy multiplication as a result of fast fission, typically $5 \leq M \leq 15$. This type of reactor serves as a breeder, creating fuel from abundant fertile resources for fissile-consuming fission power plants.

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c. The actinide burner reactor, which incorporates in its blanket heavy metal waste from fission power plants. The fusion neutrons cause transmutation and fission of the actinide wastes to reduce them to short-lived or non-radioactive isotopes. This blanket option has been proposed as a method of disposal of the long-lived nuclear waste from fission power production.

The hybrid reactor is thus a highly versatile (but potentially complex) facility. Its versatility is associated with the comparatively high energy of the D-T fusion neutron, 14.1 MeV. At this energy, the neutron exhibits strong nuclear interactions with the heavy metals and the resultant liberation of copious neutrons. As a comparison, fast fission of ^{232}Th or ^{238}U at 14 MeV produces about 4 neutrons, whereas these same reactions at 2 MeV (the energy of fission neutrons) produces only about 2.5 neutrons.

In the context of Sec. 2, the reactor configuration of interest is the fusion breeder. Such a facility would be one component of a fusion-fission power system, supplying the make-up fuel needs for (as will be subsequently shown) a number of fissile-consuming, or converter, fission reactors. As the hybrid requires only fertile materials for its operation, there are no inherent doubling-time constraints (due to fissile fuel inventories) on the rate at which individual power system could be deployed. However, there is a finite length of time required for the hybrid to inventory all of the converter reactors it supports and thus bring the system to full capacity.

4. PERFORMANCE PARAMETERS

Recently, Fortesque⁽³⁾ proposed a set of fundamental parameters to compare the fissile breeding performance of the hybrid and the fast breeder reactor. Here, the analysis of Fortesque is elaborated to reflect considerations that have been found to be of importance in our studies of the hybrid reactor.^(6,7) The purpose is to evolve parameters by which various hybrid reactor configurations can be compared on a common basis.

A schematic of the system electrical power flow is shown in Fig. 1. Here a "driven" fusion reactor is considered, that is, one which requires power input to heat the plasma. The power balance is based on one unit of input electrical power to the breeder; P_{eb} and P_{ec} represent gross electrical output from the breeder (b) and converter (c) reactors, respectively. One unit of the gross electrical output must then be recirculated to power the breeder.

The model used for the fusion breeder power flow is diagrammed in Fig. 2. Electrical power is input to the plasma heating equipment which converts this energy to plasma thermal energy at an efficiency of η_h . The power produced by fusion in the plasma is

$$P_f = \eta_h Q_p,$$

where Q_p is the plasma power amplification,

$$Q_p = \frac{\text{fusion power generated}}{\text{power to heat the plasma}}.$$

Of the D-T fusion energy liberated, 20% occurs as the kinetic energy of a charged (alpha) particle and 80% as the 14.1 MeV fusion neutron. The plasma thermal energy and the alpha energy are assumed to be recovered for thermal conversion; the fusion neutrons enter the blanket where their energy is multiplied by the factor M (blanket energy multiplication) and the resulting thermal energy is also recovered for thermal conversion. The total thermal power, P_{tb} , is converted to electrical at an efficiency η_{te} .

4.1 Power Flows

The thermal power ratio is defined as the ratio of the converter thermal power divided by the breeder thermal power,

$$R_t = P_{tc}/P_{tb}.$$

Directly, from Fig. 2, the breeder thermal power is

$$P_{tb} = \eta_h [1 + Q_p(0.2 + 0.8M)].$$

The relationship describing the fission converter reactor capacity supported by the breeder is based on a mass balance. The rate of fissile production (kg/yr) by the breeder is written as

$$\dot{m}_b = .0186 \frac{\text{kg-mole}}{\text{MW-f-yr}} A(f/n) \delta_b \hat{P}_f$$

where A is the atomic weight of the bred nucleus, (f/n) is the fissile breeding ratio (net number of fissile nuclei created per fusion neutron), δ_b is the plant

capacity factor and the unit MW_f is megawatts of fusion power. In this equation, $\hat{P}_f$ is fusion power in megawatts. The fissile consumption rate in kg/yr of the converter reactors, assuming 200 MeV per fission, is

$$\dot{m}_c = 1.64 \times 10^{-3} A(1 - C_R)(1 + \alpha)\delta_c \hat{P}_{tc}$$

Here, C_R is the conversion ratio, α is the ratio of capture to fission cross-sections, δ_c is the capacity factor and $\hat{P}_{tc}$ is thermal power in MW.

Equating the production and consumption rates and assuming $\delta_b = \delta_c$, the ratio of converter thermal power to fusion power is

$$r = P_{tc}/P_f = \frac{11.32(f/n)}{(1 - C_R)(1 + \alpha)}$$

Since (f/n) is a measure of the neutron efficiency of the breeder and the converter neutron efficiency is proportional to $[(1 - C_R)(1 + \alpha)]^{-1}$, r is a measure of the overall neutron efficiency of the power system.

Thus the thermal power of the converters is written as

$$P_{tc} = r P_f = r n_h Q_p$$

and the thermal power ratio, in terms of basic power flow parameters, is

$$R_t = \frac{r}{0.2 + 0.8H + (1/Q_p)}$$

If it is assumed that the breeder will also supply the initial fissile inventories of its associated converters, a pertinent parameter is the inventory time, τ_i , which is defined as the time required for the breeder to generate all of the initial core inventories. The inventory of the converters (kg) is expressed as

$$I_c = \hat{P}_{tc} \tau_i$$

where i is the specific inventory (kg/MW_t). Thus the inventory time, in years, is

$$\tau_i = I_c / \dot{m}_b,$$

which becomes, upon substituting for $\dot{m}_b$,

$$\tau_i = \frac{i}{1.64 \times 10^{-2} A (1 - C_R) (1 + \alpha) \delta_b}$$

The interesting aspect of this parameter is that it is dependent on only the converter nuclear characteristics. It should be noted that τ_i is the time required to bring the power system to full capacity. As the breeder will support a number of converters, say N_c , then individual reactors may start-up at intervals of τ_i / N_c and at the end of the time interval τ_i , all units will be operational.

4.2 Electrical Energy Multiplication

A general characteristic of the system shown in Figure 1 is that it is an electrical power amplifier. Therefore, an important performance parameter for the power system is its electrical power amplification factor,

$$Q_E = \frac{\text{gross electrical output}}{\text{electrical input}},$$

or

$$Q_E = P_{eb} + P_{ec}.$$

In terms of fundamental parameters,

$$Q_E = \eta_h \{ \eta_{tc} \eta_p + \eta_{tb} [1 + Q_p (0.2 + 0.6N)] \}$$

where η_{tc} is the thermal efficiency of the converters. Of interest to fusion researchers is the necessary plasma power amplification required for "break-even," or the condition where more power is produced than is consumed. Thus setting Q_E to unity, the break-even value of Q_p is

$$Q_{p*} = \frac{(1/\eta_h - \eta_{tb})}{\eta_{tc} + \eta_{tb}(0.2 + 0.8M)}.$$

A "transition" point is also defined for the fusion breeder, which is the value of plasma power amplification where the reactor provides sufficient gross electrical output to provide its own input power needs. Thus setting $P_{eb} = 1$, the corresponding value of Q_p is

$$Q_{pt} = \frac{1/(\eta_{tb}\eta_h) - 1}{0.2 + 0.8M}$$

Two different modes of operation for fusion breeders have been proposed.

1. The breeder as modeled to this point in the development, where all of the thermal power is converted to electrical. Thus, if the hybrid is a net electrical producer, it is connected to the power grid and must respond to electrical demand. This configuration will be termed "on-line."

2. The "fuel factory" configuration where the breeder would produce no electrical power, but rather obtain all of its input power needs from the output of its converter reactors, and reject all of its thermal power. This configuration might result in a reduction in design complexity and cost, and would not have to respond to demands from the power grid.

The parameters for the fuel factory can be obtained by setting η_{tb} to zero. In this case.

$$Q_E' = \eta_h \eta_{tc} \eta_p.$$

and break-even is

$$Q_{p*}' = \frac{1}{\eta_h \eta_{tc} r}.$$

Note that the class of breeder denoted as "on-line" is a net power consumer for a plasma power amplification factor less than Q_{pt} and is thus actually on-line only for $Q_p > Q_{pt}$.

4.3 Economics

To develop criteria for fusion breeders which would be economically competitive and to assess the economic implications of the two breeder configurations described in Section 4.2, a capital cost parameter is considered. As the power system will not have to purchase fissile fuel, rather only fuel cycle services, the cost of the electricity generated from the system will be strongly dominated by capital cost. Thus consider the unit capital cost (\$/kWe) of the power system,

$$C_e = \frac{C_{tc} P_{tc} + C_{tb} P_{tb}}{P_{ec} + P_{eb} - 1},$$

where C_{tc} and C_{tb} are the capital costs per unit of thermal output, \$/kWt, for the converter and breeder, respectively. This unity of cost is chosen rather than cost per kilowatt of electrical output since the breeder may not be a net electrical producer. This relation can be rearranged in the form

$$C_e = C_{ec} P_{ec} \frac{[1 + \kappa/R_t]}{P_{ec} + P_{eb} - 1}$$

where C_{ec} is the unit capital cost (\$/kilowatt electric) for the converter and κ is the relative unit capital cost

$$\kappa = C_{tb}/C_{tc}.$$

As a reference, the unit cost of the system is normalized to C_{ec} , as it is anticipated the capital cost of all of the converters will dominate the total capital cost of the power system. Thus defining the cost parameter

$$R_c = C_e/C_{ec},$$

the relation is obtained

$$R_c = \frac{1 + \kappa/R_t}{1 + (P_{eb} - 1)/P_{ec}}$$

Substituting in terms of power flow parameters for the on-line breeder,

$$R_c = \frac{1 + \kappa/R_t}{1 + \frac{\eta_{tb}}{\eta_{tc} R_t} - \frac{1}{\eta_{tc} \eta_h f Q_p}}.$$

For the fuel factory ($\eta_{tb} = 0$) the cost ratio is

$$R'_c = \frac{1 + \kappa/R_t}{1 - \frac{1}{\eta_{tc} \eta_h f Q_p}}.$$

5. DISCUSSION

To quantify these figures of merit and develop target performance parameters, two examples are considered which will be denoted as "U/Pu" and "Th/U." Assumed values (based on our research) for the power flow parameters are listed in Table 1. Values for the hybrid blanket performance parameters, M and f/n, are representative of blankets which produce enough tritium to fuel the fusion plasma; that is, they produce one tritium nucleus per fusion neutron. (8,9)

Also, the choice of the two example fuel cycles require qualification. They are not representative of the alternate fuel cycles being examined for proliferation-resistant characteristics. Rather, they are two fuel cycles which use current reprocessing technology and are well understood. The choice of these two examples is dictated by the fact that the neutronic characteristics of the alternate fuel cycles are not yet known; they are the subject of current research. (4) Thus, the examples must be regarded as simply an illustration of the quantitative characteristics of fusion-fission power systems. The alternate fuel cycles, because of their use of nuclear poisons which absorb neutrons, will suffer reduced performance as compared to the examples, the degree of reduction being dependent on the details of the specific fuel cycle under consideration. However, the fusion breeder is more capable than the fission breeder of accommodating this penalty because of the tenuous neutron balance that exists in fission breeders; fusion breeders have a comparatively abundant neutron balance.

The U/Pu example assumes a breeder with a fast-fission depleted-uranium blanket producing ^{239}Pu . The plasma heating efficiency is modest compared to the values projected for fusion reactors. (10) The converter is a light water reactor

POWER FLOW PARAMETERS

Table 1

	<u>U/Pu</u>	<u>Th/U</u>
<u>BREEDER</u>		
(f/n)	1.5	0.75
M	10	5
η_h	0.5	0.5
η_{tb}	0.35	0.35
δ_b	0.8	0.8
<u>CONVERTER</u>		
C_R	0.67	0.85
α	0.3	0.1
η_{tc}	0.35	0.35
i(kg/Mwt)	0.75	0.75

(LWR) recycling Pu from its spent fuel at a burnup of about 30 MW-d/kg. The conversion ratio used is an effective value representing the Pu make-up requirements when the core is fueled with natural uranium and Pu.⁽⁶⁾

The Th/U example assumes a breeder which produces ^{233}U from ^{232}Th . The values for f/n and M are chosen to reflect the fact that a ^{233}U producing blanket can obtain about one-half the performance of a Pu producing blanket.⁽¹¹⁾ This difference is due to the larger fast-fission cross section for ^{238}U as compared to ^{232}Th . The converter reactor is a high-gain, high-temperature gas-cooled reactor (HTGR) operating with Th as the fertile material and ^{233}U as the fissile fuel. Here, also, recycle of ^{233}U from the spent fuel is assumed.

DEPENDENT SYSTEM PARAMETERS

Table 2

	<u>U/Pu</u>	<u>Th/U</u>
r	39.6	51.5
Q_{p*}	0.10	0.085
Q_{pt}	0.58	1.12
Q'_{p*}	0.14	0.11
$\tau_i(\text{yr})$	5.6	14.4
$R_t(Q_p = \infty)$	4.83	12.3

Resulting values for some of the system parameters are listed in Table 2. To first order, plasma break-even occurs at $Q_p \approx 0.1$. The fusion breeder is self-powered ($P_{eb} = 1$) with a U blanket at a plasma power amplification of $Q_p \approx 0.6$, and for the Th blanket, $Q_p \approx 1.1$. The lower value of Q_p occurs for the U blanket because its blanket energy multiplication is larger than the Th blanket multiplication.

Even though the efficiency of producing ^{233}U is lower than that for Pu, the better performance of ^{233}U in a fission reactor results in a somewhat larger converter thermal capacity per unit of fusion power than for the U/Pu cycle. Of possible concern is the comparatively large value of τ_f for the Th/U example. However, to put this value in context, a breeder with a 1 GW fusion plasma (and thus ~ 4.7 GWt) will support eighteen 1-GW_e HTGR's, implying that during the inventory period, 1-GW_e converters can startup at approximately one year intervals. The long inventory time is a result of the large number of converters supported by the one breeder.

The thermal power ratio, R_t , is plotted as a function of the plasma power amplification, Q_p , in Figure 3 for the two examples. The magnitude of R_t increases as Q_p increases because the thermal power of the breeder is decreasing due to reduced plasma heating requirements. That is,

$$R_t = \frac{P_{nc}}{P_{nb} + P_h} = \frac{P_{nc}/P_{nb}}{1 + P_h/P_{nb}}$$

where P_{nc} and P_{nb} are nuclear powers for the converters and breeder, respectively, and P_h is heating power of the breeder. The ratio P_{nc}/P_{nb} is independent of Q_p and the ratio P_h/P_{nb} goes to zero as Q_p approaches infinity. Here the Th/U cycle also outperforms the U/Pu cycle, but the difference is larger than for the parameter r (converter thermal power/fusion power). The larger difference between the two cycles in the parameter R_t is due to the lower thermal power of the Th blanket breeder as compared to the U blanket breeder (because of lower M).

The electrical power amplification factor, Q_E , is shown in Figs. 4 and 5 for the two fuel cycles as a function of Q_p . As would be intuitively expected, Q_E increases strongly with Q_p . The on-line mode of operation achieves the best performance, as in this situation the thermal power generated by the breeder is

fully utilized. The dot (•) on the curve for on-line operation indicates the point at which the breeder makes the transition from an electrical power consumer to a net electrical producer (Q_{pt}). The difference in electrical power amplification for on-line operation with the two cycles is quite small (~10%), and they achieve $Q_E \sim 10$ at $Q_p \sim 1$. For the U/Pu example, the fuel factory mode of operation incurs about a 15% penalty at $Q_p \sim 1$ as compared to the on-line option. For the Th/U example, this penalty is only about 10%.

In Figure 6, the relative system capital cost factor, R_c , is plotted as a function of Q_p for the Th/U cycle with the breeder operating in the on-line mode. Here, the relative unit capital cost, κ , is treated as a parameter, varying from 1 to 3. For $Q_p \geq 1$, where the breeder is a net power producer, very attractive economic performance is indicated and is comparatively insensitive to breeder capital costs. Even for $Q_p = 0.5$, R_c is less than 1.5 for $\kappa \leq 2.5$. In Figure 7, the same parameters are plotted, but for the fuel factory mode.

To compare the various mode of operation, a system cost of $R_c = 1.25$ is chosen as an economically competitive target. The values of κ and Q_p needed to achieve $R_c = 1.25$ are plotted in Figure 8 for the two breeder configurations. The on-line reactor is competitive at $Q_p \approx 0.5$ if its unit capital cost were the same as the converter ($\kappa = 1$), but only a modest increase in plasma performance to $Q_p \approx 1$ would permit the breeder to be competitive at about 2.5 times the unit capital cost of the converter. For the fuel factory configuration, this reactor must have a cost reduction of about a factor of two as compared to the on-line reactor to achieve comparable economics with the same plasma performance, Q_p .

The system capital cost parameter, R_c , for the U/Pu cycle with an on-line breeder is plotted in Fig. 9 as a function of Q_p with κ as a parameter. Here, because a fewer number of converters are supported by the breeder than if it used the Th/U cycle, it must achieve better performance (Q_p) or lower cost (κ) for system capital costs equivalent to the ²³³U-producing breeder. The values of κ and Q_p required to achieve the target system cost of $R_c = 1.25$ are shown in Fig. 10 for the two configurations. Here, the fuel factory breeder requires quite optimistic capital costs. At $Q_p = 1$, the on-line breeder requires a unit capital cost ratio of $\kappa \approx 1.5$ as compared to a value of $\kappa \approx 2.5$ for the Th/U cycle.

The result that the Th/U cycle will admit higher fusion breeder capital costs (κ) than the U/Pu cycle does not imply that the ^{233}U breeding reactor is inherently more economically attractive. Our results to date, based on specific point designs and thus not completely general, indicate that the Th blanket fusion breeder is more expensive than the U blanket breeder.⁽⁶⁾ Therefore, caution is advised in the interpretation of the economic comparison between the two cycles.

6. CONCLUDING REMARKS

For the fusion breeder it may be concluded that the criteria for implementation are highly favorable. Specifically,

- scientific feasibility, or break-even, occurs at a plasma power amplification of $Q_p \approx 0.1$, and
- for $Q_p \sim 1-2$, the fusion breeder exhibits attractive commercial prospects for relative unit capital costs in the range $\kappa \sim 1.5-2.5$.

Two major fusion experiments are now under construction, the Tokamak Fusion Test Reactor (TFTR) and the Mirror Fusion Test Facility (MFTF), which will both begin operation in 1981. TFTR is projected to achieve $Q_p \sim 1$, and for MFTF, $Q_p \sim 0.1$. Success in this upcoming step in the Magnetic Fusion Program will thus provide two independent demonstrations of the plasma conditions necessary for fusion breeder scientific feasibility or break-even. A modest upgrade of these conditions, in perhaps one additional experiment, would provide the plasma physics base for development and commercialization of the fusion breeder.

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7. REFERENCES

- (1) D. Dreyfuss, B. Augenstein, W. Mooz and P. Sher, "An Examination of Alternate Nuclear Breeding Methods," Rand Corp., Rept. R-2267-ERDA (in preparation).
- (2) Proceedings of the Second DMFE Fusion-Fission Reactor Meeting, Washington, D. C. (November, 1977), in preparation.
- (3) P. Fortesque, "Comparative Breeding Characteristics of Fusion and Fast Reactors," Science 195, 1326 (1977).
- (4) "Nonproliferation Alternative Systems Assessment Program Plan," Department of Energy (1977).
- (5) L. M. Lidsky, "Fission-Fusion Symbiosis: General Considerations and a Specific Example," Proc. BNES Nuclear Fusion Reactor Conf., Culham Laboratory, U.K. (1969), paper 1.2.
- (6) D. J. Bender, "Mirror Hybrid Reactor Optimization Studies," Proc. US-USSR Sympos. on Fusion-Fission Reactors, Lawrence Livermore Laboratory (1976), CONF-760733 p. 37.
- (7) D. J. Bender and G. A. Carlson, "System Model for Analysis of the Mirror Fusion/Fission Reactor," Lawrence Livermore Laboratory, Rept. UCRL-52293 (1978).
- (8) J. D. Lee, "Neutronics Analysis of a 2500 Mwt Fast Fission Natural Uranium Blanket for a DT Fusion Reactor," Proc. of First Topical Meeting on the Technology of Controlled Thermonuclear Fusion, San Diego, CA (1974), CONF-740402-P1, p. 223.
- (9) J. D. Lee, "Blanket Design for the Mirror Fusion/Fission Hybrid Reactor," Proc. US-USSR Sympos. on Fusion-Fission Reactors, Lawrence Livermore Laboratory (1976), CONF-760733, p. 27.
- (10) J. H. Fink, W. L. Barr and G. W. Hamilton, "A 225-MW Neutral Injection System for a Mirror Fusion-Fission Hybrid Reactor," Nuclear Fusion 15, 1067 (1975).
- (11) A. G. Cook and J. A. Maniscalco, "²³³U Breeding and Neutron Multiplying Blankets for Fusion Reactors," Nuclear Technology 30, 5 (1976).

System Electrical Power Flow

Figure 1

Fusion Breeder Power Flow

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10