INFLUENCE OF STARTUP, SHUTDOWN AND STAGED POWER OPERATION ON TANDEM MIRROR REACTOR DESIGN

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ABSTRACT

With the maturity of conceptual fusion reactor designs it is important to develop comprehensive scenarios for the startup and shutdown of fusion plants and to investigate physics and engineering requirements and design constraints and their implications. We then focus on the impact of such considerations on the operation of tandem mirror fusion reactors (TMR's). Brief examples from both the fission and conventional power industries are discussed. TMR plant operation is divided into an initial commissioning phase and four subsequent generic phases: (1) Phase IA: cold shutdown; (2) Phase IB: hot shutdown; (3) Phase II: system testing, plasma startup and standby power operation; (4) Phase III: staged power operation; and (5) Phase IV: rated power operation. Power ascention through these phases is explained in terms of the operation of two major systems: (1) the plasma technology and support system, and (2) the heat transport system. Physics and engineering constraints, subsystem interactions, and design implications are discussed throughout the paper using the Mirror Advanced Reactor Study (MARS) as the specific example.

I. INTRODUCTION

Conceptual fusion reactor designs have generally considered fusion system characteristics and design issues for operation at full power. Yet experience with power plants of other types indicates this is hardly the case. Many design features and operational procedures are determined by transients during the startup and shutdown. Moreover, subsystems and components are usually optimized for maximum efficiency at full power. We report here on the general implications of startup, shutdown, and staged power operation on the design of tandem mirror fusion reactors. In particular, the Mirror Advanced Reactor Study (MARS)[1] is used as the specific reactor example. Our work on the reactor physics aspects of startup and staged power operation is reported in reference 2 while details of our engineering analysis are reported in reference 3.

Two broad objectives of the present study are:

(1) Identify and analyze procedures during fresh (first time) startup.
(2) Evaluate system responses to frequent power transients during subsequent startup or shutdown operations. The emphasis here is on the interaction between physics and engineering operation, designs, and constraints.

Generally after completion of construction, a startup program may extend up to 2 years for large, first-of-a-kind, power plants. Later, and with experience, this may be reduced to 9 months. The key objectives of a startup testing program of a fusion plant are:

(1) To demonstrate that components and systems operate and function as designed.
(2) To obtain test results showing that the plant can be safely operated.
(3) To verify via testing that the plant can be shutdown in an orderly fashion.
(4) To show that plant operating and emergency procedures are sufficient.

Design modifications, auxiliary power requirements and engineering and physics constraints must therefore be considered in a startup program.

In the following section, we discuss examples from the power industry, identifying areas of concern during startup, shutdown, or staged power operation. In section III, we outline the proposed major phases of fusion plant operation, beginning with initial commissioning and proceeding to full power operation. In section IV, we discuss the engineering constraints and their impact on plasma operation and reactor design for the specific case of tandem mirrors.

II. EXAMPLES FROM THE POWER INDUSTRY OF STARTUP REQUIREMENTS

In this section, we illustrate the stages followed during the initial startup of selected systems from the power industry. We sumarize briefly the startup requirements and procedures for Light Water Reactors (LWR's), Liquid Metal Fast Breeder Reactors (LMFBR's), and coal (or oil) fired steam power plants.

A. Pressurized Light Water Reactors[4,5]

Acceptance criteria are used during startup testing to verify that the plant operates as expected from both a performance and safety standpoint. Testing is performed under safe operating conditions rather than "accident" or "safety analysis" conditions. Thus, the results of some tests are only indirectly related to the safety analysis. In addition, many tests are performed to determine operational parameters that are not safety related. A startup test program can be divided into four main categories: (1) preoperational testing phase; (2) plant heat-up phase; (3) startup phase; and (4) power ascention phase.

1. Pre-operational testing phase: A program is conducted to insure that each specific system and component has been properly installed and will function as designed at ambient tempertures and pressure.

2. Plant Heat-up Phase: Plant initial conditions are established. The NSSS is in the "cold shutdown mode". In this condition, the pumps are off, decay heat (if any) is removed, and the steam generator is filled to 100% water level. For example, in the San Onofre PWR Nuclear Power Plant the system temperature is gradually increased and the pressure is also increased to operating conditions of 2235 psig by maintaining charging flow greater than letdown flow. When the pressure is between 400 and 425 psig and stable, the reactor coolant pumps are started to begin the Reactor Coolant System (RCS) heatup. This phase of operation lasts for approximately one day, and the heat-up rate is controlled to less than 30°F/hour due to stress and power availability limitations. The reactor is brought to criticality at zero power at the end of this phase.

3. Startup Phase: Functional checks are performed for nuclear instrumentation to assure their reliability. The power is increased until the "point of adding heat" is reached. This is the power level (about 1% power) where the reactor is producing sensible heat. The reactor operator holds 1% power while the turbine-driven main feed pump is warmed and placed in service. The reactor power is then increased to about 5% power in preparation for rolling the main turbine. However, actual turbine roll does not occur until the 20% power plateau is reached. Increasing reactor power will cause the steam dump valves to open further and dissipate the excess heat.

4. Power Operation: Reactor power is increased following turbine load. It is important during this phase to prevent axial xenon oscillations by adequate boron control. The power is increased at a rate of 2-5%/hour to insure that fuel element failure does not occur. This rate is essentially dictated by the interaction between the fuel and the cladding during power transients. In order to avoid significant Pellet-Clad-Interaction (PCI), sufficient time must be given to allow for creep relaxation of differential expansion stresses.

The power is increased to 20%, where a power plateau is established. At this level, the in-core power detectors will sense power variations. The heat exchanger and turbines are designed to run at 100% power and the entire secondary cycle will be unstable at power levels less than 20%.

Power ascention is accomplished within 20-30 weeks, with five major power plateaus. Each plateau has its own temperature/pressure and trips associated with it. The plateaus are at 20%, 50%, 80%, post 80% and 100% of full power.

B. Liquid Metal Fast Breeder Reactors[6]

In the initial startup of a typical LMFBR such as the proposed Clinch River Breeder Reactor Plant (CRBRP), operation is generally divided into zero-power conditions, and power production condition. In the cold condition, the Reactor System (RS) and the Heat Transport System (HTS) are evacuated and back filled with argon to remove impurities at temperature. The RS + HTS are then heated during the preheat condition phase from the dry, argon filled, cold iron condition to 400 °F at a rate of 3°F/hour using the electrical heaters of the Piping and Equipment Electrical Heating and Control System (P&EEHCS). The Steam Generator System (SGS) is then heated to 400°F by using the Auxiliary Steam Boiler (ASB) and the heat input from recirculation pumps.

During the fueling condition phase, the RS and HTS are filled with sodium at 400°F. This temperature is maintained by the electric heaters. The sodium pumps are started on their pony motors (~ 10% sodium flow), and pre-operational tests are performed. The hot standby phase is begun by heating the reactor and heat transport system to 600°F at a rate of 50°F/hour. The SGS is heated to 600°F and a pressure of 1450 psig is established in the steam drum. The turbine is simultaneously warmed, and the sodium flow rate is established at 40% of maximum value.

A low power phase is initiated by increasing reactor power to various levels in a manner similar to that outlined for LWR's. However, the heatup rate is much faster in this case, on the order of 150°F/hour. The turbine speed is increased while dumping the excess steam at low power. At roughly 15% of rated power, bypass steam is secured and the turbine is loaded. The reactor power is further increased. At 40% power, the HTS temperature drops are established at 40% flow power in the HTS and SGS. In the last stage, all systems are raised to their performance levels for full rated power output.

C. Coal and Oil Fueled Power Plants[7]

The startup procedure for a fossil fueled power plant is a well programmed event and generally simpler than that for fission reactors. Placing a cold boiler in service requires firing at low heat input for a long period to avoid thermal expansion difficuties and the possible overheating of superheaters or reheaters. Low pressure units ($P < 200$ psi) without superheaters require about one hour for cold startup. Larger, high pressure units may require 4 to 6 hours. Because the heat input is low during startup, special fuel requirements are made. For instance, light fuel oils are preferred (Nos. 1 or 2) but fuel no heavier than No. 6 is allowed. Soot buildup and the possibility of a boiler fire is a major hazard during this heating phase. Natural gas can be used for initial heating but extreme care must be taken to avoid a momentary interruption in the flame. Due to low furnace temperatures the flame may not reignite and an unignited gas buildup and possible furnace explosion could occur.

III. MAJOR PHASES OF FUSION PLANT OPERATION

The operation of fusion plants can be conveniently divided into an initial commissioning phase and four phases which repeat in order as the plant is shutdown and subsequently restarted. These phases are listed in Figure (1). Phase 0 is Initial Plant Commissioning and occurs once when the plant is in the just-constructed condition. The first phase is the reactor in the shutdown mode of which two types are possible. A Phase IA or Cold Shutdown Mode is expected to occur infrequently and would require that the blanket and other power related components be completely shutdown. In the case of a liquid metal cooled blanket, the coolant would be drained and separately stored. A Phase IB is a Hot Shutdown Mode in which the power conversion components and their coolants are maintained near ready operating conditions of temperature and pressure, but there is no plasma operation.

Phase II is a system testing, plasma startup and standby power phase in which major engineering system performance tests are made, the plasma is started and the reactor brought to a low power standby operating state. Typically, the fusion power generated in Phase II is less than 5% of the rated power.

In Phase III, Staged Power Operation, the reactor power is raised in stages until rated power operation is achieved. For purposes of system testing and licensing requirements, the reactor will operate for an extended period at fractions of full reactor power. Finally, Phase IV, Rated Power Operation, is when the reactor produces power continuously at its rated design or licensed power level.

For purposes of further analysis and discussion, it is helpful to divide the reactor engineering systems into two general classes as listed on Figure (2). The two classes, Plasma Technology and Support Systems, and Heat Transport Systems encompass all subsets of individual systems. Listed on Figure (2) are examples of subsets falling under each heading. From this, one can readily identify subsystems which can be operated and tested independently of others and those where common operation is required. As examples of such interactions during initial commissioning or during a reactor restart, testing of a liquid metal cooled blanket is likely to require operation of the magnet system. Testing of the first wall cooling system may require plasma operation to establish the surface heat loading and appropriate thermal and pressure stresses in the wall. The location and formation of the vacuum boundary may depend on the thermal state of the blanket and shield. These interactions and the various phases of plant operation, using MARS as an example, are discussed in the following subsections.

A. Phase 0: Initial Commissioning

A.1. Plasma Technologies: Pre-Plasma Operation

Plasma technologies include those support systems directly related to plasma operation. They therefore include the various magnet systems and their refrigerators, power supplies and controls, the plasma heating systems including neutral beams, RF, their power supplies and controls, the vacuum, gas processing and refueling systems, including tritium processing and control, and the direct convertor system in the case of a tandem mirror.

The operation of these systems can generally be tested prior to actually producing plasma. The possible exceptions are the RF and direct convertor systems. In particular, coupling of the RF power into the plasma depends on the performance of the launching structure in the presence of plasma. By contrast, an NBI system can be tested by taking power on the beam dumps and plasma absorption of NBI power is straightforward relative to RF. Performance of the direct convertor depends upon establishing a particular potential drop from the plasma to the collector, thereby also requiring plasma for complete testing. Thus, in the pre-plasma stage, system performance tests will be carried out on the magnets and the gas handling systems, and partially on the plasma heating and direct conversion systems.

A.2. Heat Transport System: Pre-Plasma Operation

The heat transport system includes in-vessel components such as beam dumps, limiter/divertor collectors, antennas and direct energy convertor, the first wall-blanket system which includes the structure, tritium breeding material, coolant and neutron multiplier, the reflector-shield system and coolant, the tritium recovery and recycling system, the primary loop including piping, pumps and valves, and the secondary loop including the heat exchanger, the steam generator, and the turbine.

The subsystems of the heat transport system are tested at various levels. First, many of the components such as pumps, valves, and beam dumps can be tested prior to final assembly. After plant construction is completed, the subsystems are tested in the Pressurized Cold Condition (PCC) where leaks are detected at rated pressures. The completion of this phase is followed by testing in the Pressurized Hot Condition (PHC). Due to stress redistribution around cracks, it is expected that leak rates can be quite different at rated temperatures and pressures in the PHC mode of testing. Even though the majority of tests on the heat transport subsystems are done to insure good performance at rated parameters, a variety of tests are designed at various power levels to guarantee the safe opration of the plant in anticipated accidents. Of course it is not expected that accident conditions are simulated during such tests, but rather that mild transients are induced and the test results are extrapolated to more accident-like conditions. A detailed discussion on specific tests is given in section III.D.

A.3. Initial Plasma Operation

During initial commissioning and following all system tests in a pre-plasma stage, first plasma is produced. Details of a specific plasma initiation and startup sequence to bring a TMR plasma to a standby power mode is given in a separate paper.[2] Suffice it to say here that the objective during this initial commissioning phase is to establish plasma performance parameters with a minimum production of fusion power (perhaps even zero). The purpose is to test all plasma support technologies, such as direct convertors and limiter/pumping systems, in the presence of plasma, establish the plasma performance characteristics of a full TMR plasma, including the proper potential distribution, confinement parameters, and plasma parameters in each individual cell. This should all be accomplished while keeping to a minimum the generaton of induced radioactivity. Operating with ordinary hydrogen is favored and will allow direct, hands-on-maintenance of reactor components, diagnostics, and controls. It is expected in a reactor that this testing will take one to two months, much less than in present experiments.

For tandem mirrors, the use of hydrogen leads to a lower $n\tau$ in the plugs but this can readily be overcome using the heating systems. More difficult may be the operation of plasma when ion cyclotron resonance frequency (ICRF), ω_{CD} heating is employed. In TMR's, ICRF is used in the central cell for startup. Since the ICRF system is generally tuned to $2\omega_{CD}$ (which is equal to ω_{CH}), it will not heat a pure hydrogen plasma. Using deuterium during this phase will lead to some neutron production and a careful tradeoff is required. (In tokamaks with ICRF as the dominant heating source, hydrogen operation may be precluded except for tests using only ohmic heating.)

At the end of this initial commissioning phase, all subsystems have been tested, and plasma performance is verified. The plant can then be commissioned for power operation.

B. Phase I: Shutdown/Zero Power Mode

This mode of operation encompasses Phase IA; cold shutdown, and Phase IB; hot shutdown. During a fresh startup, and in the infrequent case of drained blanket modules, startup commences from "cold-iron" conditions. The primary piping as well as blanket modules must be gradually brought to operating temperature. This heat-up phase may take 1-2 days, depending on available auxiliary heating power and thermal stress limitations. In the MARS design, for example, we have estimated a heat-up period of 30 hours using a helium gas pre-heat system.[3]

Once the entire primary system is conditioned to a uniform temperature of 350°C, the LiPb coolant is pumped out of its storage tank and allowed to fill the primary system. This is accomplished by first filling half of the primary coolant piping system, then the blanket modules bottom-to-top, and finally the remaining half of the piping. This process proceeds at low pump speeds to minimize pump-induced vibrations. The LiPb coolant is subsequently kept at the uniform temperature of about 350°C by pump heat. At this stage, the plant is ready for low power physics testing.

In the hot shutdown mode (Phase IB), start-up period is expected to be much shorter than Phase IA. The hot shutdown mode can occur frequently due to various system failures. It is estimated that 30-50 system shutdowns per year will occur in a TMR.[3] When total fusion power is lost, the coolant outlet temperature decreases at the rate of 10°C/second without pump speed compensation. We have developed a Primary Temperature Regulation and Pre-heat System (PTR&PS) for the response to fusion power fluctuations.[3] This system consists of a gas heater, gas blower, electric resistance strap heaters, coolant overflow surge tank, coolant dump tank, and associated instrumentation and control. In case of a total loss of fusion power, pump speeds (and coolant flow rates) are adjusted to keep a uniform coolant temperature of 350°C everywhere in the primary. The time variation of decay afterheat is also taken into account. If pump failure occurs, off-site power is lost, or shutdown is extended, the electric resistance strap heaters are energized to maintain coolant temperature at 350°C and the entire coolant volume is drained into an external dump tank. The LiPb coolant is kept molten in the tank by an external immersion-type electric heater, or allowed to freeze if shutdown is expected to be long.

C. Phase II: Standby Mode and Phase III: Staged Power Increases

The standby mode and staged power increases to full power are best achieved in a tandem mirror by controlling the central cell plasma radius. We report on the details elsewhere[2], but this conclusion has been arrived at after examining numerous other alternatives. We find that altering the plasma radius while maintaning central cell density and temperature leads to optimum system performance. In particular, the plasma Q is essentially constant for any power level above 20% of rated, full power. Further, we have found that when a conceptual TMR design employs a high field hybrid copper-superconducting magnet combination, as in the MARS design,[1] to produce 24 T in the choke coils at each end of te central cell, the recirculating power fraction increases sharply at reduced operating power levels. We find that when a TMR employs drift orbit pumping, as is also the case in MARS[1], plasma operation may be optimum without using a copper insert[2]. The reason is that at any level of operating power, the power consumed by the copper coil more than off-sets the improved plasma performance obtained with the higher field choke coil.

The main plasma time constants under ordinary operating conditions are obtained from the $n\tau$ value and the fusion product slowing down time. In general, these range between 0.5 and 2 seconds, short compared to engineering system time constants. The latter will thus dictate the rate at which power is increased or decreased in going from one operating level to another. We expect that the plasma will proceed quasi-statically to different power levels, i.e., the plasma will always have thermal equilibrium parameters even as controlled power changes are implemented. There appears to be no intrinsic reason preventing the plasma from tracking a power change path as prescribed by engineering constraints.

At standby power, the reactor plasma operates using only deuterium fuel and the heat transport system is maintained by heat from the pumps. The steam generator and turbine are likely to be unstable if run below 10-20% of rated power. We have assumed no electricity is generated from the blanket thermal cycle when the fusion power is less than 20% of rated power. During standby mode, plasma parameter tests are made to insure proper plasma operation. Key parameters include:

i. density, temperature, and potential, both axially and radially in the system;
ii. plasma power;
iii. plasma beta limit;
iv. plasma potential control (and plasma size control) with bias on the direct convertor.

Establishing that the plasma performs according to design implicitly means that performance tests with plasma will be carried out for many of the plasma technology support systems. For TMR's, these again include the neutral beams, (ICRF and ECRF (and the coupling efficiencies of each), the barrier pumping systems, and the direct convertor.

Power ascention tests are expected to last for 20-30 weeks, including approximately 3 weeks at full power. There are five major plateaus for power ascention[3], at 20%, 50%, 80%, post 80%, and 100% of full power.

Following low power physics tests, engineering tests are performed at the aformentioned power plateaus. Generally, three tests are performed on the heat transport system: turbine trip, loss of load, and loss of flow. These three tests are performed to demonstrate:

a. that the models used for design and safety analysis adequately represent the system at those high power levels.

b. that the entire fusion system performs as designed under these transient conditions.

The parameters and system performance to be monitored include:

i. pressure, level, and flow in the LiPb expansion tank.
ii. Heat Transport Coolant System (HTCS) temperatures and pressures.
iii. Steam Generator (SG) pressure level.
iv. performance of the main and auxiliary feedwater control system.
v. plasma power.
vi. charging and letdown flows.
vii. pump speeds and pressure drops.
viii. strain gauge measurements for fatigue and vibration analysis at critical components.

Following initial commissioning and after shutdowns of extended duration, tests are performed at various power levels to verify design and to assure safety during power escalation. The primary tests expected to be performed in a TMR are:

0-20% power

Plant data are recorded for selected parameters during given intervals ranging from minutes to hours. The feedwater Control System (FWCS) is actuated at a power level of ~5% to ensure adequate water compensation and a balanced flow to the steam generators occurs at about 20% power. ΔT measurements are calibrated and correlated to fusion power through the enthalpy rise across the blanket and coolant flow rate.

20% power plateau

During this power plateau, initial turbine roll is established. Accomplished during this plateau are turbine warmup and loading, checking for noises, vibrations, control system operation, etc. Also, manual trip is initiated and transient parameters recorded. The Steam Bypass Control System (SBCS) capacity is also checked at this point for safety reasons. Plant chemistry and primary coolant radioactivity are monitored, baseline chemistry and corrosion data is gathered at the 20%, 50%, 80%, and 100% power plateaus. Calorimetric measurements for power are also performed at each plateau. Offsite power is removed, at 40% power, by isolating the startup transformers. The turbine is tripped and blackout conditions are maintained for ~1/2 hour. Ability to achieve hot shutdown mode (Phase IB) is verified, and selected parameters are measured to insure that emergency power systems function properly.

50% power plateau

Although the dose behind the biological shield is continuously monitored, its effectiveness is critically evaluated by verifying neutron leakage rates. The ability to perform a shutdown from outside the control room is established at this power level. Adequate initiation and performance will be demonstrated at power levels ranging from 50% to 100% power. This is accomplished by activating the cut-back system and demonstrating that the resultant power reduction and distribution are as designed.

80% power plateau

All plant system pumps are tripped at 80% power, and selected parameters are monitored to verify natural circulation. A detailed analysis of natural circulation in MARS has been performed by Taghavi and Ghoniem[8].

100% power plateau

A loss of load transient is initiated at 100% power. Selected parameters are monitored to verify proper automatic plant response to the transient.

Warranty Run

The warranty run is performed as part of initial commissioning and fresh plant start. Generally, one can expect the plant to operate at rated thermal output for about two weeks. During the run, calorimetrics are performed daily.

In order to limit the deleterious effects of thermal transients caused by a rapid change in power, the blanket flux level and its rate of change are monitored by the plant instrumentation and control (I&C) system.[9] As a performance requirement, the response time of sensors should be short enough to assure that rapid flux changes are monitored. In addition, the delay between the flux/flux change measurement requiring plant shutdown, and the time a trip action is taken should be minimal. This includes the flux sensors response time and its associated circuitry. The flux sensors could be fission counters or B-10 compensated ionization chambers located in thimbles at the back edge of the blanket. Neutron flux leakage at this location can be taken as an indication of blanket power. This should be calibrated with ΔT measurements in both the primary and secondary for various power levels.

At high power operation, the I&C system should also assure that sustained operation will not occur with the blanket running dangerously close to its design limit. Fusion system shutdown is initiated, for example, when the signal from the flux monitoring system exceeds a predetermined setpoint that is dictated by acceptance criteria. Furthermore, sufficient I&C redundancy is required in the I&C system design to assure that single random sensor failures are prevented. The I&C system should also permit periodic testing and calibration of sensors, since extended operation in a radiation environment degrades the efficiency, sensitivity and response time of sensors due to radiaton hardening. Work on the I&C system is reported elsewhere.[9]

IV. ENGINEERING CONSTRAINTS AND IMPLICATIONS FOR PLASMA OPERATION AND REACTOR DESIGN

It has become apparent that the longest time scales are dictated by engineering constraints rather than physics performance. The details of such constraints are explained in a companion paper.[3] In summary, the rate of fusion power variation must be slow enough to meet the following limitations: (1) Stress and material compatibility limits. Very fast power variations are not allowed to avoid shock waves in the blanket system and to avoid rapid differential thermal expansion of the coolant-breeder-structure system; (2) Auxiliary power requirement limits. It has been shown, based on available auxiliary power, that electric resistance pre-heating requires a prohibitively long time, and that gas pre-heating for the primary-blanket system takes about 1-2 days; (3) Mechanical limits. The inertia of pumps and valves is responsible for the slow response of the primary coolant system to rapid power variations. Pump startup, for example, must provide extra torque for fluid acceleration, acceleration of rotating parts, and MHD startup losses.

Plasma operation will therefore track the slower time scales dictated by the engineering constraints. In general, the blanket and piping system design must accommodate differential expansion caused by temperature excursions. A Primary Temperature Regulation and Pre-Heat System (PTR&PS) should be incorporated as a part of the overall power plant. Finally, design tests must show that the system can adequately respond to a limited number of induced power transients, without major failures of components.

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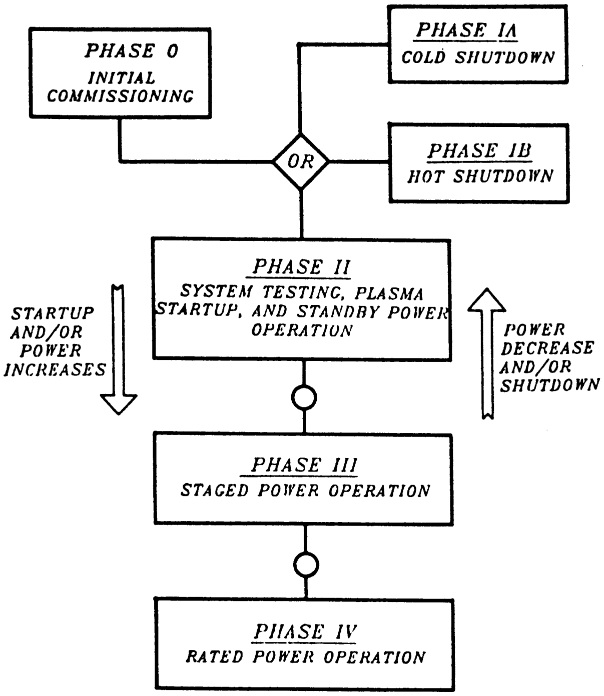

Fig. 1. The general phases of fusion power plant operation.

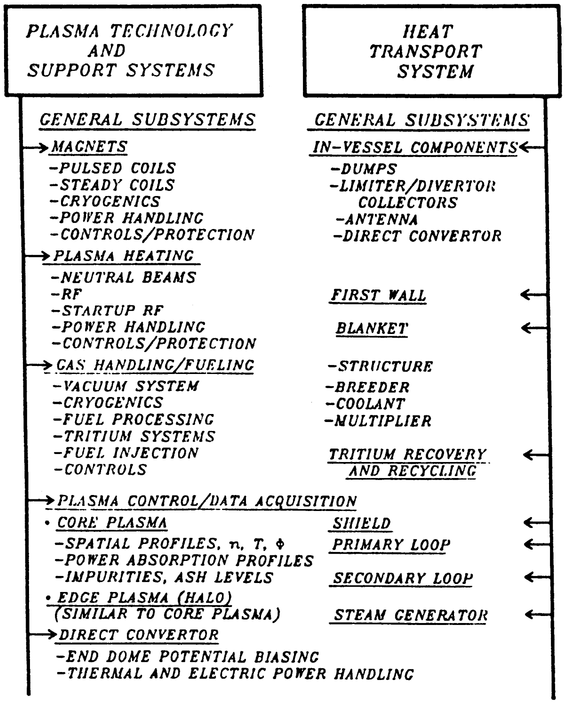

Fig. 2. The general systems in a tandem mirror fusion reactor. Most system categories are general enough to apply to any fusion reactor concept.