2. PROGRAM OBJECTIVES

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2.1. INTRODUCTION

Fusion reactor conceptual design has become a mature research field and results from system studies research have greatly influenced the direction of the physics and technology elements of the fusion energy program. The reactor studies during 1970's were focused on central power stations with electric power outputs of 1000 to 2000 MWe. These designs were usually based on superconducting magnets to minimize the recirculating power. They shared basic disadvantages of large stored magnetic energy and fusion power cores (FPC) which were very large in volume and heavy in mass (FPC comprising of first wall, blanket, shield, magnets, plasma support systems, vacuum vessel, and related structures). These resulted in systems with large total power output, high direct capital cost, and low power density. These designs raised the perception that fusion power, if feasible, would only come in units of large size and low power density and as a result would be quite expensive.

More recent reactor studies now seek ways to use the past experience and move toward a more affordable, competitive, and "attractive" fusion reactor. One of the approaches to the new generation of reactor design is the compact reactor option [1-3]. The main feature of a compact reactor is a FPC with a high mass power density (MPD). MPD is defined as the ratio of the net generated electric power to the total mass of the FPC (in units of kWe/tonne). The increase in mass power density is achieved by increasing the plasma power density and neutron wall loading, by reducing the size and mass of the FPC using a thin blanket and resistive magnet coils, and by increasing the blanket energy multiplication ratio.

Even though compact designs push toward very high mass-power-density regimes, increasing realism in conceptual reactor design and costing has moved even the "conventional" designs toward smaller FPCs and higher mass-power-densities. As an example, one might begin in 1974 with UWMAK-I [4] at 20 kWe/tonne to STARFIRE [5] in 1980 and MARS [6] at 50 kWe/tonne to GENEROMAK [3] at 100-200 kWe/tonne and compact reversed field pinch reactor, CRFPR [2] at 800 kWe/tonne. The mass power density and FPC power density of several of these and other conceptual fusion reactor designs, together with fission PWRs, are shown in Fig. 2.1.-1 [1]. A compact reactor thus strives toward a system with FPCs comparable in mass and volume to the heat sources of alternative fission power

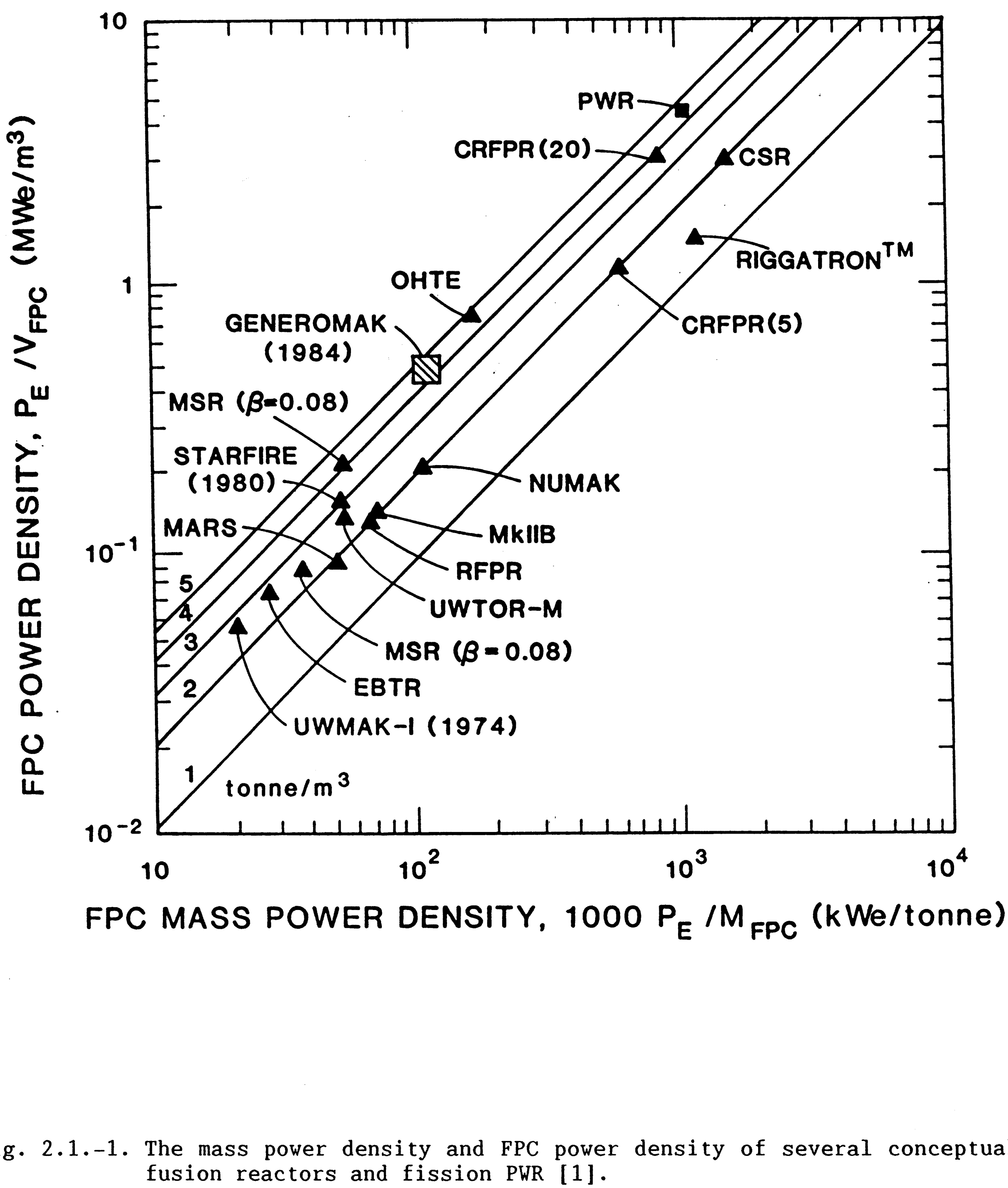

Fig. 2.1.-1. The mass power density and FPC power density of several conceptual fusion reactors and fission PWR [1].

plants with mass power densities in the range 500-1000 kWe/tonne. These arguments have recently prompted the suggestion that a mass power density of 100 kWe/tonne be a threshold goal for fusion reactor design [1].

There are other potential benefits for compact systems. In addition to improved economics, the FPC cost in a compact reactor is a small portion of the plant cost, and therefore, the economics of the reactor would be less sensitive to large changes in the unit cost of FPC components or the plasma performance. Moreover, since a high mass-power-density FPC is smaller and cheaper, a rapid development program at lower cost is possible, changes in FPC design would not introduce large cost penalties, and the economics of learning curves can be exploited.

Mass power density however, is only one general measure of the potential economic competitiveness of a fusion reactor. Other factors should also be considered in the search for an optimum and "attractive" fusion reactor. One can summarize the general features of an "attractive" fusion reactor as:

1. Potential for a range of power output. Reduced net power output and associated lower capital investment (investment at risk) not only makes the plant more attractive, it can also permit an affordable development pathway to bring the fusion option to commercial fruition.
2. Affordable and competitive total cost, unit direct cost ($/kWe), and cost of electricity (mills/kWeh). This can be achieved by:
   A. increasing mass power density,
   B. increasing overall plant efficiency,
   C. reducing or combining the functions of reactor subsystems and plasma support technologies.
3. Simplified overall FPC design.
4. Reduced engineering constraints (e.g., magnetic fields, stresses, magnetic stored energy), simple subsystem design (e.g., large duct blanket, single coolant), and combined subsystem functions (e.g., integrated blanket/coil) can lead to safe and reliable operation, reduce the forced outages, allow eased and rapid maintenance, and as a whole can drastically increase the plant availability.
5. Built-in enhanced safety and environmental features. This reduces the use of safety-specific systems and reduced probability of accidents with either serious public health or capital cost consequences.
6. Reduced rad-waste disposal requirements. Use of low-activation

materials reduces the quantity and quality of radioactive waste and eases the long term waste disposal issues.

It should be emphasized that some of these goals and features of an "attractive" fusion reactor may not be achievable simultaneously, and trade-offs are required. The effect of these trade-offs can be assessed only through specific and detailed design.

2.2. OBJECTIVES

The TITAN program is a multi-institutional effort to determine the potential of the Reversed Field Pinch (RFP) magnetic fusion concept as a compact, high-power-density, and "attractive" fusion energy system. The primary program objectives are:

1. Determine the technical feasibility and key developmental issues of an RFP fusion reactor, especially at high power density.
2. Determine the potential economics, cost of electricity, safety and environmental features of such a high power density RFP reactor.

Auxiliary objectives are:

1. Establish the major technical features of an RFP reactor.
2. Develop detailed conceptual designs for the major subsystems and components.
3. Assess the degree of extrapolation between the present data base in RFP physics and in technology and the physics/technology requirements of an RFP reactor.
4. Determine the technical features and parameters of RFP devices required at key steps in a development program.
5. Develop innovative design approaches for a high mass-power-density fusion system.

The RFP has inherent characteristics which allow it to operate at very high mass power densities. This potential is available because the main confining field in a RFP is the poloidal field, which is generated by the large toroidal current flowing in the plasma. This feature results in low field at the external magnet coils, high plasma beta, and very high engineering beta (defined as the ratio of the plasma pressure to the square of the magnetic field strength at the coils) as compared to other confinement schemes. Furthermore, sufficiently low magnetic fields at the external coils permits the use of normal coils while Joule losses remain a small fraction of the plant output. This option can permit a thinner blanket/shield. In addition, high current density in the plasma allows ohmic heating to ignition, eliminating the need for auxiliary heating equipment. Also, RFPs promise the possibility of efficient current drive systems based on low frequency oscillation of poloidal and toroidal voltages and the RFP relaxed states theory. Finally, RFP confinement concept allows arbitrary aspect ratio, and the circular cross section of plasma eliminates the need for plasma shaping coils.

These inherent characteristics of the RFP allow it to meet, and actually far exceed, the threshold value of 100 kWe/tonne. As a result, the TITAN study also seeks to find potentially significant benefits or drawbacks that can be obtained by operating well above the mass-power-density threshold of 100 kWe/tonne. Therefore, the program has chosen a high neutron wall loading as the reference case in order to force the issue of engineering practicality at high mass power density. However, the program has put strong emphasis on safety and environmental features and maintainability, reliability, and availability issues. These features and constraints are incorporated into the FPC design from the beginning.

2.3. SAFETY AND ENVIRONMENTAL ASPECTS

The TITAN study is aiming towards a fusion reactor with four major features: minimum cost of electricity (COE), high availability, design simplicity, and improved safety. These goals and features may not be achieved simultaneously and trade-offs are required. For example, if add-on safety equipment are needed, the design can become more complex and have lower availability and higher cost. On the other hand, if the safety features are incorporated in the design from the beginning, the reactor can potentially be inherently safe, simpler, and have higher availability and lower cost. The TITAN study, therefore, has designated the safety as an integral part of the design activity with the safety features built in the design from the beginning.

In order to define a clear direction for the TITAN design approach in terms of improved safety, we have adopted the following definition of levels of safety assurance, suggested by S. Piet of EG&G [7] and adopted by ESECOM [8]:

Level 1. "Inherent Safety". The public is protected from prompt or early fatalities even under incredible events. The approach to this level can be by controlling the radiological hazard inventory and/or by controlling energy sources existing to disperse the inventory even under incredible events.

Level 2. "Large-Scale Passive Protection". This approach relies only on natural properties (e.g., natural circulation) and the integrity of large scale components (e.g., containment building integrity, the pool for pool designs). The public is adequately protected even if some severe phenomenon breaks all the cooling pipes and other small scale components.

Level 3. "Small-Scale Passive Protection". This approach relies on natural properties (e.g., natural circulation) if the small-scale geometry of the reactor is maintained. Seismic qualification will be needed to ensure that such behavior as natural circulation continues as planned in the event of an accident.

Level 4. "Active Safety". Active engineered systems must function to prevent off-site prompt or early fatalities in the event of a major accident. Safety analysis, testing, and qualification of safety equipment is needed to ensure the safety of public is adequately protected at all times.

Based on the above discussion, the TITAN study focuses on design concepts that can achieve passive safety, aiming at the level 2 of safety assurance (large-scale passive safety).

For the treatment of radioactive waste, TITAN aims at design concepts with 10CFR61 Class-C waste rating (i.e, qualified for shallow land burial). For a Class-C rating, the dose delivered to an individual inadvertently constructing a house on the waste-disposal site and living there continuously starting at any time more than 100 years after the wastes were generated (the "intruder dose") must never exceed 500 mrem/yr. The intruder dose includes contributions from the consumption of vegetables, meat, and milk produced on the site.

2.4. MAINTENANCE APPROACH AND AVAILABILITY

An important potential benefit of operating at very high mass power density is the possibility of single-piece maintenance scheme. In such a maintenance scheme, the FPC is replaced as a single torus including the plasma chamber, first wall, blanket, shield , and toroidal field coils. The potential benefits of such a replacement scheme as compared to a more "conventional" modular approach are:

1. The reactor torus is made of a few factory-fabricated pieces that are assembled on-site, in a non-nuclear environment, and into a fully operational unit.
2. FPC can undergo full operational, non-nuclear testing before installation in the rector building.
3. The number of connections that must be made or broken in the nuclear environment is minimized.
4. The scheduled maintenance period is shortened because of reduced replacement time and shorter restart period with increased confidence level.
5. The recovery procedure from unscheduled events is more rapid and standard with the replacement of the entire reactor torus with a stand-by pretested torus.
6. This approach can also accommodate FPC improvement throughout the plant life and allows full benefit from learning curves economics.

These potential benefits of the single-piece maintenance approach should ultimately translate into an increase in plant availability and directly improve the economics of the plant. The TITAN program seeks to quantify and demonstrate these potential benefits.

2.5. PROGRAM APPROACH

To achieve the design objectives of the TITAN study, the program was divided into two phases, each roughly one year in length: the Scoping Phase and the Design Phase. The objectives of the scoping phase were: to define the parameter space for a high-MPD RFP reactor; to explore a variety of approaches of major subsystems; to select at most two major design approaches consistent with high MPD; and to reach an intermediate stage which includes preliminary engineering design and integration. The two major approaches identified during the scoping phase would then be the subject of more detailed and in-depth analysis during the design phase.

The first half of the scoping phase was devoted to wide-range scoping studies of a large variety of different design concepts. The purpose of this period was to "let a thousand flowers bloom," that is to encourage creativity and the generation of new ideas. The guidelines followed were to find concepts that held the potential to form the basis for an attractive compact RFP reactor. Those ideas and concepts that seemed promising were selected for more detailed analysis during the latter part of the scoping phase. The impact of various design options were routinely evaluated and analyzed through system studies. At the end of the scoping phase, good preconceptual design definitions were in hand for reactor subsystems to initiate the design phase.

Section 3 discusses the scoping phase activities. Detailed technical analysis and results of plasma engineering, system analysis, divertors, reactor engineering, and FPC engineering efforts are given respectively in Sec. 4 through 8. Finally, Sec. 9 contains a summary of results of the scoping phase and directions for the design phase activities.

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