3. SCOPING PHASE ACTIVITIES

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3.1. INTRODUCTION

The TITAN study is striving towards a fusion reactor with four major features: minimum cost of electricity (COE), high availability, design simplicity, and improved safety and environmental features. To achieve these design objectives, 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 mass power density (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 major two approaches identified during the scoping phase then would 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-ranging 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. During this period, the TITAN design team members were encouraged to participate in "brain-storming" and a very large number of ideas were put forward. For example, twelve different fusion power core (FPC) designs were proposed (Sec. 3.2), different magnetics approaches were considered, and various options for impurity control and current drive systems were studied.

Those ideas and concepts that seemed promising were selected for more detailed analysis during the latter part of the scoping phase. For example, of the twelve proposed FPC designs, four were selected for further study. These four were the lithium loop with integrated-blanket-coil (IBC) design, the aqueous blanket, the helium-cooled ceramic reactor, and the molten salt pool approach. Simultaneously, scoping phase activities were carried out to analyze the plasma fusion core, to design plasma support technologies (e.g., magnets, impurity control system), and to investigate reactor engineering issues such as power conversion systems, maintainability, and availability. The impact of various design options were routinely evaluated and analyzed through system studies. At the end of the scoping phase, preconceptual design definitions were sufficient for major reactor subsystems to initiate the design phase. Detailed technical analysis and results are given in the Sec. 4 through 8 of this report.

Of particular importance are the FPC design concepts for high power density systems that were proposed during the scoping phase. These concepts are summarized in the following sections.

3.2. FPC CONCEPTS

During the first half of the Scoping Phase, the TITAN design team members were encouraged to participate in the "concept brainstorming," and a very large number of ideas were put forward. Several of these were sufficiently attractive to warrant consideration as a distinct scoping study FPC design concept. These design concepts can be loosely categorized by the general FPC design as:

1. Loop-type,
2. Pool-type,
3. Loop-in-pool.

Major features of these concepts are presented in the following subsection.

3.2.1. Loop-Type Concepts

The coolant in these concepts flows in "loops" around the plasma chambers. The major feature of these designs is the capability to efficiently remove the thermal power.

3.2.1.1. Lithium Coolant

The Blanket Comparison and Selection Study (BCSS) [1] identified the combination of liquid-lithium coolant and breeder with vanadium-alloy structure as the most attractive blanket concept for both tokamaks and tandem mirrors. The functions of the coolant and breeder are combined in this design. To achieve a high thermal efficiency, a Li/Li/V blanket is designed such that the primary coolant outlet temperature at the heat exchanger is in the neighborhood of 550°C. Because of the favorable heat-transfer characteristics of liquid lithium, high neutron wall loadings can be effectively handled in such a design. Several design variations were considered for TITAN.

Liquid-Lithium Loop. This approach is a straightforward adaptation of the BCSS Li/Li/V concept to the RFP. This concept offers the promise of high neutron wall load, good efficiency and a simple configuration. Lithium flow parallel to the dominant poloidal magnetic field eases the concerns of MHD effects compared with tokamak designs. Good tritium breeding, control and recovery are expected. A variant of this concept, the liquid lithium IBC loop, was selected for more detailed evaluation.

Liquid-Lithium IBC Loop. The Integrated Blanket Coil (IBC) concept proposed by Steiner [2] matches well with the liquid-lithium loop design. By simply flowing current through the lithium in the blanket loop, the blanket can serve the function of the toroidal-field (TF) coils. This combination simplifies the reactor by eliminating a separate TF coil and also recovers the coil ohmic power for conversion to electricity. This concept was selected as one of the four concepts for more thorough evaluation during the scoping phase, and is described in Sec. 8.2.

Beryllium-Lithium-Tritium Zone (BLiTZ). A variant of the IBC concept is called BLiTZ [3]. In this concept, the toroidal (and poloidal) field coils could be of a fairly conventional solid copper conductor construction, but would be cooled by liquid lithium. Beryllium could be added to the coil, possibly even replacing the copper completely, to achieve adequate tritium breeding. This approach offers lower coil resistance and power consumption and better tritium breeding than the lithium IBC. Preliminary investigation of this concept for TITAN indicated that the overall performance was about the same as the liquid-lithium IBC loop design. The additional complication and materials uncertainty of the BLiTZ concept were not warranted, and this approach was not considered further.

3.2.1.2. Lithium-Lead Loop

Lithium-lead alloy ($Pb_{83}Li_{17}$)is much less chemically reactive than lithium and offers excellent neutron and energy multiplication for good tritium breeding and energy performance. The self-cooled lithium-lead blanket was rated second blanket for tandem mirrors in the BCSS [1], and was selected for the blanket (but not first wall) of the Compact Reversed Field Pinch Reactor (CRFPR) design [4]. However, the large MHD pressure drops and modest heat transfer prevented the use of PbLi to cool the TITAN first wall at high neutron wall loads (20 MW/m^2). To avoid the complexity of different coolants for the blanket and first wall, and the safety concerns of water and liquid metals in proximity, the PbLi blankets were not pursued for TITAN.

3.2.1.3. Helium-Gas-Cooled Direct Cycle

This concept relies on a high temperature, low-activation structural material (e.g., SiC or carbon/carbon composites) in the first wall and blanket. The first wall and blanket are cooled by a high pressure, high-temperature helium-gas cooling medium. The objective of this design is to achieve good thermal efficiency in a direct gas cycle, thus eliminating the need for an intermediate heat exchanger (IHX). Helium cooling, therefore, offers a number of advantages for fusion and several helium-cooled blankets scored well in the BCSS.

Several "conventional" helium-cooled high temperature solid breeder blankets were considered. In addition, an innovative design concept emerged that uses a helium-cooled high-temperature solid breeder blanket with all ceramic structure. This approach would achieve a truly low activation design with excellent safety characteristics. It appears this concept would meet level 1 of safety assurance (i.e., inherent safety). This concept was called the Fusion Inherently Safe Ceramic (FISC) Reactor, was evaluated during the TITAN scoping phase, and is described in Sec. 8.5.

3.2.1.4. Water Loop

Many previous reactor designs have selected water cooling. Water has the benefit of an extensive technology base, derived from the fission LWR industry and is the coolant best suited to high-heat-flux conditions. A disadvantage is the modest thermal efficiencies (30-35%) that are accessible using water because of pressure limitations. Two advanced dual-media system were considered in order to increase the efficiency of the water design.

Dual Media. The idea of using water coolant with another working fluid as a topping or bottoming cycle was considered as a possible means to improve the efficiency. Freon or ammonia can be used as a bottoming cycle to squeeze a few more points of efficiency from a water system, but the extra capital cost of the bottoming cycle is not justified; COE actually increases. A major limitation of this cycle is best demonstrated by the shape of the thermodynamic cycle (T-S) diagram. A condensing bottom cycle fits better with a cycle like the gas turbine (Rankine cycle) that rejects heat over a range of temperature than a condensing water cycle.

Binary-Vapor-Cycle Loop. In this design, water is used in a separately cooled first wall. In the blanket, a lithium or lithium-bearing compound is encased in metal cladding for tritium breeding. Potassium coolant is used as a heat transfer medium. The potassium coolant leaves the blanket in the vapor phase and goes directly to a gas turbine, thus eliminating the need for an IHX and also reducing the MHD pressure drop. The water provides heat for the standard Rankine cycle, and the potassium vapor provides the working fluid for the topping part of the binary cycle. High thermal efficiencies (42%) can be achieved in this binary cycle. Major disadvantages are the complexity of the combined K/H_2O system and the potential safety concerns from using liquid metal and water in the blanket, which together led to the rejection of this concept.

3.2.2. Pool-Type Concepts

In the pool-type configuration, the plasma chamber and the first wall are submerged in a pool of coolant. This configuration is simple since the pool acts as a replenishable blanket and shield. Furthermore, the pool design promises the potential for inherent safety due to the high heat capacity of the pool. The major disadvantage of the pool concepts is the difficult and uncertain coolant flow configuration, which limits the heat-flux capabilities of the first wall. Several pool-type concepts were evaluated for TITAN design.

3.2.2.1. Liquid-Metal Pool

This concept is fashioned after the liquid-metal pool design of the Phénix and Superphénix French reactors and shows all of the potential benefits of the pool-type concepts. However, the eddy currents induced in the electrically-conducting coolant in the pool interferes with the plasma transient operations (e.g., startup, oscillating-field current-drive). Although resistive baffles can be used in the pool to reduce the eddy currents, such a modification would also inhibit free coolant flow in the pool and would significantly negate the advantageous features of a pool-type design.

3.2.2.2. Molten-Salt Pool

Molten lithium salts offer the potential for a self-cooled blanket that can operate at high temperature and low pressure. They are non-conducting and thus avoid MHD pressure drop concerns. Mixtures of LiF and BeF2 ("FLiBe") have been used for several fusion reactor designs. The FPC is submerged in a pool of FLiBe. The FLiBe will fill the space between the first wall and magnets and will, therefore, provide adequate magnet protection. A FLiBe-to-FLiBe intermediate heat exchanger (IHX) is also located in the pool. The IHX is needed for reasons of safety and tritium containment. Since the working fluid is FLiBe on both sides of the IHX, the IHX can continue to operate with small leaks. If pumps are also submerged in the pool to generate a FLiBe flow upward around the first wall and downward through the IHX for the purpose of heat transport, the need for a primary loop is eliminated. The molten salt pool concept was selected for evaluation and is described in Sec. 8.4.

3.2.2.3. Water Pool

The water-pool concept is the synthesis of several attractive ideas. Steiner proposed the use of an aqueous solution of a lithium compound as the breeder and coolant [5]. The pool reactor concept has emerged as an option with potential for passive safety. The TITAN program investigated combining these to obtain an aqueous solution pool. The initial idea was to place the entire reactor within a high pressure pool, with the high-temperature lithium-solution coolant/breeder separated from the low-temperature pure water pool by an insulated but non-pressure-bearing flow loop. The major disadvantage of this concept was the structural requirements of the high-pressure water pool. To reduce this requirement, the design evolved into a "loop-in-pool" design with a high-pressure, high-temperature loop located within a low-pressure, low-temperature pool (Sec. 3.2.3 and Sec. 8.3).

3.2.3. Loop-in-Pool Concept

The need for a pool is dictated by the desire to mitigate the effects of severe accidents (i.e., loss-of-coolant accident, LOCA, and loss-of-flow accident, LOFA). However, the use of a coolant pool is limited by the maximum heat flux that can be handled by the first wall. The working fluid must be pumped at high velocity (hence, high pressure) near the first wall. This approach has severe limits on the maximum first-wall surface heat flux as compared with a loop-type design.

One viable approach is to combine the desirable features of both pool-type and loop-type concepts into one design, leading to the aqueous-solution blanket design. In this approach, an aqueous solution of lithium nitrite is used as the coolant and breeder medium. The aqueous lithium salt blanket allows convenient external control of the tritium in the blanket. During the initial system-commissioning phase, pure water could be used to allow plasma and heat transport system testing without the complicating effects of tritium production. The salt could then be gradually added to achieve the desired operating levels of tritium production. This concept promises good safety characteristics, simple design features, and capability for high power density. The aqueous-solution design was selected for more detailed evaluation and described in Sec. 8.3.

3.3. FPC CONCEPT EVALUATION

During the first half of the scoping phase of the TITAN study, several design concepts were considered which were listed in the previous sections. Of those designs, four were selected for more detailed evaluation. These four concepts were those that appeared to offer the greatest promise to achieve the program goals in an optimum way. These four are the lithium-loop IBC design, the aqueous-solution pool concept, the helium-cooled ceramic reactor, and the molten salt pool design.

More detailed designs were then undertaken for each of the four concepts. Self-consistent mechanical configurations were laid out, and analysis was performed to determine thermal and structural design windows for each concept. The maximum neutron wall load and first-wall surface heat flux was determined for each design approach. The tritium breeding and energy multiplication characteristics were determined and optimized. The thermal efficiency and recirculating-power requirements were determined. Critical issues were identified for each concept. At the end of the scoping phase, a good preconceptual design definition was available for each of the four concepts. The results of this evaluation are summarized in Sec. 8.

At the end of the scoping phase, a program consensus was reached to narrow the number of designs to be pursued during the design phase of the study to two. The decision was necessary because of inadequate resources to pursue all four designs. The decisions on which of the two concepts to pursue were very difficult to make, since all four concepts have attractive features. The lithium-loop design promises excellent thermal performance and is one of the main concepts being developed by the US/DOE blanket technology program. The water design promises excellent safety features and use of more developed technologies. The helium-cooled ceramic design offers inherent safety and excellent thermal performance. The molten-salt pool design is the only low pressure blanket and promises passive safety.

Ultimately, the IBC lithium-loop and the aqueous loop-in-pool concepts were selected for detailed conceptual design and evaluation in the design phase of the TITAN program. The choice was made primarily on the capability to operate at high neutron wall load and high surface heat flux. The lithium-loop and aqueous loop-in-pool designs appear able to operate at a neutron wall loading of 20 MW/m^2 and a surface heat flux of 5 MW/m^2. The helium-ceramic and molten-salt designs appear to be limited to a maximum first-wall heat flux of no more than 1.5 to 2 MW/m^2 corresponding to a neutron wall load of 7 MW/m^2 at f_{RAD} of unity (i.e., all of the alpha power is radiated and deposited uniformly on the first wall). While this latter value is a significant power density, a major element of the charter of the TITAN program is to investigate engineering approaches to and the technical feasibility of high-power-density fusion reactor designs. Therefore, the choice not to pursue the helium-ceramic design and molten-salt designs should in no way denigrate these concepts. These concepts offer high performance and attractive features when used at lower wall loads. The TITAN program recommends that these concepts be pursued in other design studies.

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