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Introduction and synopsis of the TITAN reversed-field-pinch fusion-reactor study

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The TITAN reversed-field-pinch (RFP) fusion-reactor study has two objectives: to determine the technical feasibility and key developmental issues for an RFP fusion reactor operating at high power density; and to determine the potential economic (cost of electricity), operational (maintenance and availability), safety and environmental features of high mass-power-density fusion-reactor systems. Mass power density (MPD) is defined as the ratio of *net* electric output to the mass of the fusion power core (FPC). The FPC includes the plasma chamber, first wall, blanket, shield, magnets, and related structure.

Two different detailed designs TITAN-I and TITAN-II, have been produced to demonstrate the possibility of multiple engineering-design approaches to high-MPD reactors. TITAN-I is a self-cooled lithium design with a vanadium-alloy structure. TITAN-II is a self-cooled aqueous loop-in-pool design with 9-C ferritic steel as the structural material. Both designs use RFP plasmas operating with essentially the same parameters. Both conceptual reactors are based on the DT fuel cycle, have a net electric output of about 1000 MWe, are compact, and have a high MPD of 800 kWe per tonne of FPC. The inherent physical characteristics of the RFP confinement concept make possible compact fusion reactors with such a high MPD. The TITAN designs would meet the U.S. criteria for the near-surface disposal of radioactive waste (Class C, 10CFR61) and would achieve a high Level of Safety Assurance with respect to FPC damage by decay afterheat and

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radioactivity release caused by accidents. Very importantly, a "single-piece" FPC maintenance procedure has been worked out and appears feasible for both designs.

Parametric system studies have been used to find cost-optimized designs. to determine the parametric design window associated with each approach, and to assess the sensitivity of the designs to a wide range of physics and engineering requirements and assumptions. The design window for such compact RFP reactors would include machines with neutron wall loadings in the range of 10–20 MW/m^2 with a shallow minimum COE at about 18 MW/m^2. Even though operation at the lower end of the this range of wall loading (10–12 MW/m^2) is possible, and may be preferable, the TITAN study adopted the design point at the upper end (18 MW/m^2) in order to quantify and assess the technical feasibility and physics limits for such high-MPD reactors. From this work, key physics and engineering issues central to achieving reactors with the features of TITAN-I and TITAN-II have emerged.

1. Introduction

The TITAN research program is a multi-institutional [1–11] 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 from economic (cost of electricity), safety, environmental, and operational viewpoints.

In recent reactor studies, the compact reactor option [12–15] has been identified as one approach toward a more affordable and competitive fusion reactor. The main feature of a compact reactor is a fusion power core (FPC) with a mass power density in excess of 100 to 200 kWe/tonne. Mass power density (MPD) is defined [12] as the ratio of the net electric power to the mass of the FPC, which includes the plasma chamber, first wall, blanket, shield, magnets, and related structure. The increase in MPD is achieved by increasing the plasma power density and neutron wall loading, by reducing the size and mass of the FPC through decreasing the blanket and shield thicknesses and using resistive magnet coils, as well as by increasing the blanket energy multiplication. A compact reactor design, therefore, strives toward a system with an FPC comparable in mass and volume to the heat sources of alternative fission power plants, with MPDs ranging from 500 to 1,000 kWe/tonne and competitive cost of energy.

Other potential benefits of compact systems can be envisaged 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 will be less sensitive to changes in the unit cost of FPC components or the plasma performance. Moreover, since a high-MPD FPC is smaller and cheaper, a rapid development program at lower cost should be possible. Furthermore, changes in the FPC design will not introduce large cost penalties, and the economics of learning curves can be readily exploited throughout the plant life.

The RFP has inherent characteristics that allow it to operate at very high MPDs. This potential is available because the main confining field in an RFP is the poloidal field, which is generated by the large toroidal current flowing in the plasma. This feature results in a low field at the external magnet coils, a high plasma β, and a very high engineering β (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 permit the use of normal coils, while joule losses remain a small fraction of the plant output. This option allows a thinner blanket and shield. In addition, the high current density in the plasma allows ohmic heating to ignition, eliminating the need for auxiliary heating equipment. Also, the RFP concept promises the possibility of efficient current-drive systems based on low-frequency oscillations of poloidal and toroidal fluxes and the theory of RFP relaxed states. The RFP confinement concept allows arbitrary aspect ratios, and the circular cross section of the plasma eliminates the need for plasma shaping coils. Lastly, the higher plasma densities particularly at the edge, together with operation with a highly radiative RFP plasma, significantly reduce the divertor heat-flux and erosion problems.

These inherent characteristics of the RFP [16] allow it to meet, and actually far exceed, the economic threshold MPD value of 100 kWe/tonne. As a result, the TITAN study also seeks to find potentially significant benefits and to illuminate the main drawbacks of operating well above the MPD threshold of 100 kWe/tonne. The program, therefore, has chosen a minimum cost, high neutron wall loading of 18 MW/m^2 as the reference case in order to quantify the issue of engineering practicality of operating at high MPDs. Furthermore, two different detailed designs, TITAN-I and TITAN-II, have been produced to demonstrate the possibility of multiple engineering-design approaches to high-MPD reactors. TITAN-I is a self-cooled lithium design with a vanadium-alloy structure. TITAN-II is a self-cooled aqueous loop-in-pool design with 9-C ferritic steel as the structural material. Both designs would use RFP plasmas operating with essentially the same parameters. Both conceptual reactors are based on the DT fuel cycle, have a net electric output of about 1000 MWe, are compact, and have a high MPD of 800 kWe per tonne of FPC. The TITAN study also put strong emphasis on safety and environmental features in order to determine if high-power-density reactors can be designed with a high level of safety assurance and with low-activation material to qualify for Class-C waste disposal.

An important potential benefit of operating at a very high MPD is that the small physical size and mass of a compact reactor permits the design to be made of only a few pieces, allowing a single-piece maintenance approach [17,18]. Single-piece maintenance refers to a procedure in which all components that must be changed during the scheduled maintenance are replaced as a single unit, although the actual maintenance procedure may involve the movement, storage, and reinstallation of other reactor components. In the TITAN designs, the entire reactor torus is replaced as a single unit during the annual scheduled maintenance [11]. The single-piece maintenance procedure is expected to result in the shortest period of downtime during the scheduled maintenance period because: (1) the number of connects and disconnects needed to replace components will be minimized, and (2) the installation time is much shorter because the replaced components are pretested and aligned as a single unit before commitment to service. Furthermore, recovery from unscheduled events will be more standard and rapid because complete components will be replaced and the reactor brought back on line. The repair work will then be performed outside the reactor vault.

The operating space of a compact RFP reactor has been examined using a comprehensive parametric systems model that includes the evolving state of knowledge of the physics of RFP confinement and embodies the TITAN-I and TITAN-II engineering approaches [3–10]. Two key figures of merit, the cost of electricity (COE) and mass power density (MPD), are monitored by the parametric systems model and are displayed in Fig. 1 as functions of the neutron wall loading. The figure shows that the COE is relatively insensitive to wall loadings in the range of 10 to 20 MW/m^2, with a shallow minimum at about 19 MW/m^2. The MPD is found to increase monotonically with the wall load. For designs with a neutron wall load larger than about 10 MW/m^2, the FPC is physically small enough that

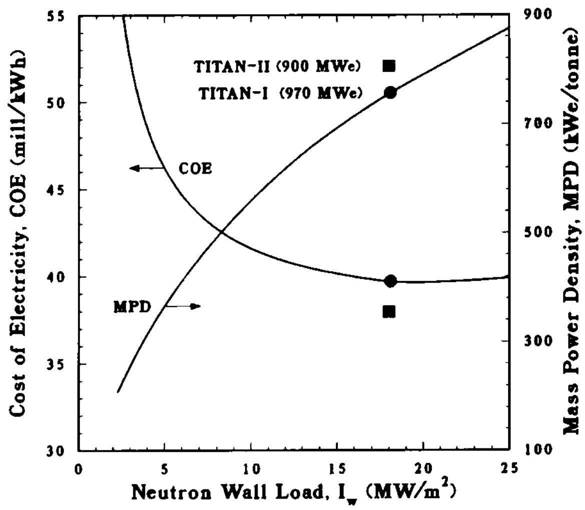


Fig. 1. The COE and MPD as functions of neutron wall loading for the TITAN-class RFP reactors. TITAN-I (filled circle) and TITAN-II (filled squares) reference design points are also shown.

single-piece FPC maintenance is feasible. These considerations point to a design window for compact RFP reactors with neutron wall loading in the range of 10 to 20 MW/m^2. The TITAN-class RFP reactors in this design window have an MPD in excess of 500 kWe/tonne, and an FPC engineering power density in the range of 5 to 15 MWt/m^3; these values represent improvements by factors of 10 to 30 compared with earlier fusion-reactor designs. The FPC cost is a smaller portion of the total plant cost (typically about 12%) compared with 25% to 30% for earlier RFP designs [14,15]. Therefore, the unit direct cost is less sensitive to related physics and technology uncertainties.

Near-minimum-COE TITAN-I and TITAN-II design points, incorporating distinct blanket thermal-hydraulic options, materials choices, and neutronics performances have been identified in Fig. 1. The major operating parameters of the TITAN reactors are summarized in Table 1. In order to permit a comparison, the TITAN reference design points have similar plasma parameters and wall loadings, allowing for certain plasma engineering analyses to be common between the two designs.

In the following sections, the major features of the TITAN designs are reviewed and the physics requirements for achieving this class of reactors are examined. Greater detail can be found in the final report of the

Table 1
Operating parameters of TITAN fusion power cores

	TITAN-I	TITAN-II
Major radius (m)	3.9	3.9
Minor plasma radius (m)	0.60	0.60
First-wall radius (m)	0.66	0.66
Plasma current (MA)	17.8	17.8
Toroidal field on plasma surface (T)	0.36	0.36
Poloidal β	0.23	0.23
Neutron wall load (MW/m^2)	18	18
Radiation heat flux on first wall (MW/m^2)	4.6	4.6
Primary coolant	Liquid lithium	Aqueous solution
Structural material	V-3Ti-1Si	Ferritic steel 9-C
Breeder material	Liquid lithium	$LiNO_3$
Neutron multiplier	none	Be
Coolant inlet temperature (°C)	320	298
First-wall-coolant exit temperature (°C)	440	330
Blanket-coolant exit temperature (°C)	700	330
Coolant pumping power (MW)	48	49
Fusion power (MW)	2301	2290
Total thermal power (MW)	2935	3027
Net electric power (MW)	970	900
Gross efficiency	44%	35%
Net efficiency	33%	30%
Mass power density, MPD (kWe/tonne)	757	806
Cost of electricity, COE (mill/kWh)	39.7	38.0

TITAN study [2] and other papers in this special issue [3–10].

2. TITAN plasma engineering

The TITAN RFP plasma operates at steady state using oscillating-field current drive (OFCD) [19,20] to maintain the 18 MA of plasma current. This scheme utilizes the strong coupling, through the plasma relaxation process that maintains the RFP profiles [21], between the toroidal and poloidal fields and fluxes. Detailed plasma-circuit simulations have been performed that include the effects of eddy currents induced in the FPC. The calculated efficiency of the OFCD system is 0.3 A/W delivered to the power supply (0.8 A/W delivered to the plasma).

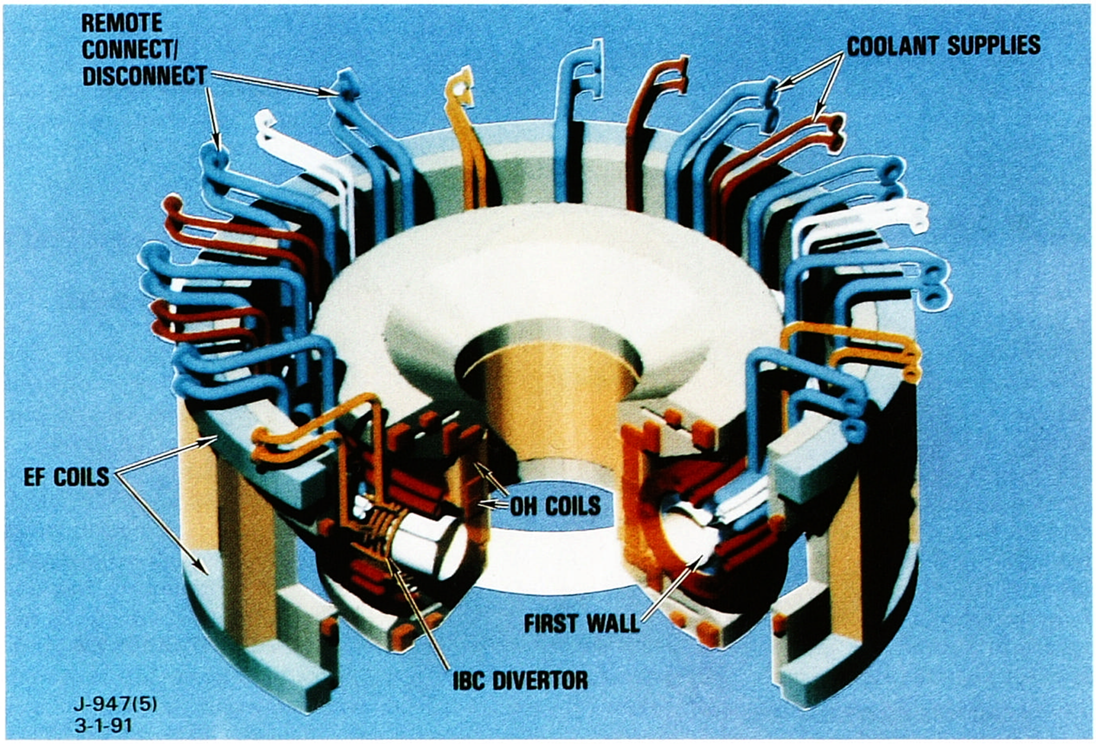
The impurity-control and particle-exhaust system consists of three high-recycling, toroidal-field divertors. The TITAN designs take advantage of the β-limited confinement observed in RFP experiments [16,22,23] to operate with a highly radiative core plasma, deliberately doped with a trace amount of high-Z Xe impurities. This distributes the surface heat load uniformly on the first wall (4.5 MW/m^2). Simultaneously, the heat load on the divertor target plates is reduced to less than ~ 9 MW/m^2. The ratio of impurity density to electron density in the plasma is about 10^{-4}, Z_{eff} is about 1.7, and 70% of the core plasma energy is radiated.

The "open" magnetic geometry of the divertors, together with the intensive radiative cooling, leads to a high-recycling divertor with high density and low temperature near the divertor target ($n_e \simeq 10^{21}$ m^{-3}, $T_e \simeq 5$ eV) relative to the upstream separatrix density and temperature ($n_e \simeq 2 \times 10^{20}$ m^{-3}, $T_e \simeq 200$ eV). The radial temperature profile is calculated to decay sharply to 2 eV near the first wall. Negligible neutral-particle leakage from the divertor chamber to the core plasma and adequate particle exhaust are predicted. The first-wall erosion rate is negligibly small because of the low plasma temperature and high density at that location.

The plasma start-up scenario for TITAN reactors can be divided into three phases: a 1–10 ms formation phase (up to 0.2 MA of plasma current), a fast current ramp (2–3 s, up to 10 MA), and a slow ramp to full plasma current. The plasma is ohmically heated to ignition during the current ramp-up phases when the impurity control system and equilibrium-field (EF) control are fully active. The required poloidal and toroidal fluxes for start-up are produced by the normal-conducting ohmic-heating (OH) coils with a bipolar swing. The TITAN start-up power is obtained directly from the grid (500 MW maximum) and no on-site energy storage is required. A pair of superconducting EF coils produce the required vertical field. These

Fig. 2. The TITAN-I fusion power core.

Fig. 3. Cutaway view of the TITAN-I fusion power core.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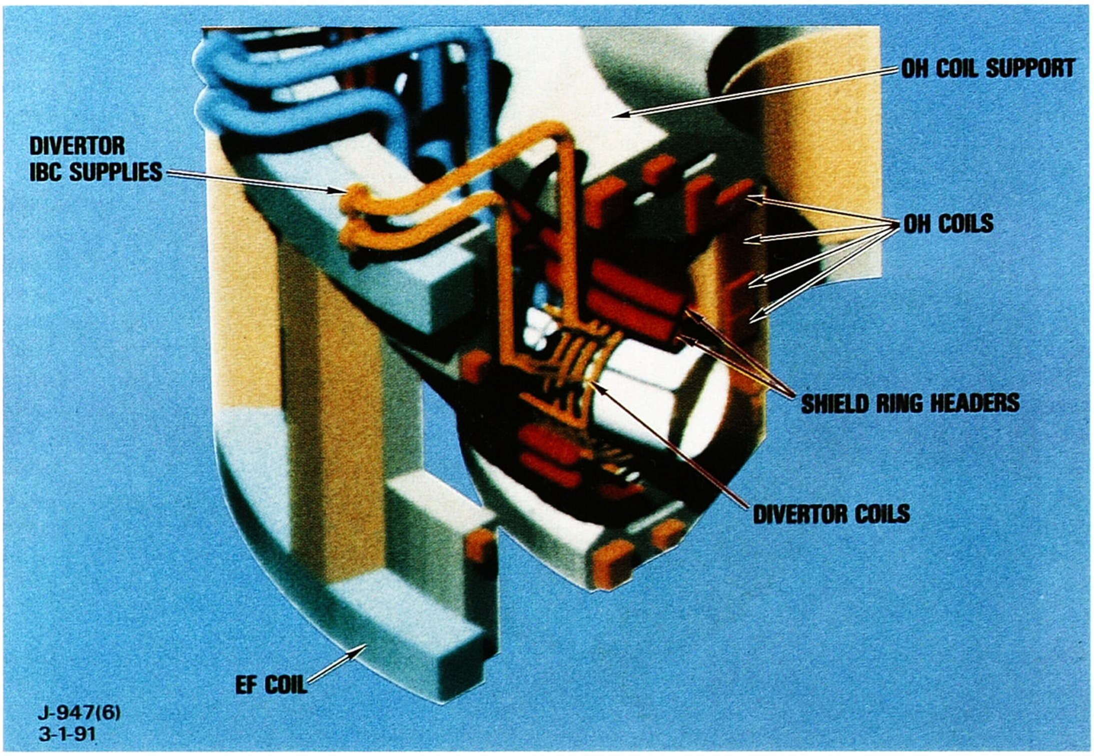
OH COIL SUPPORT
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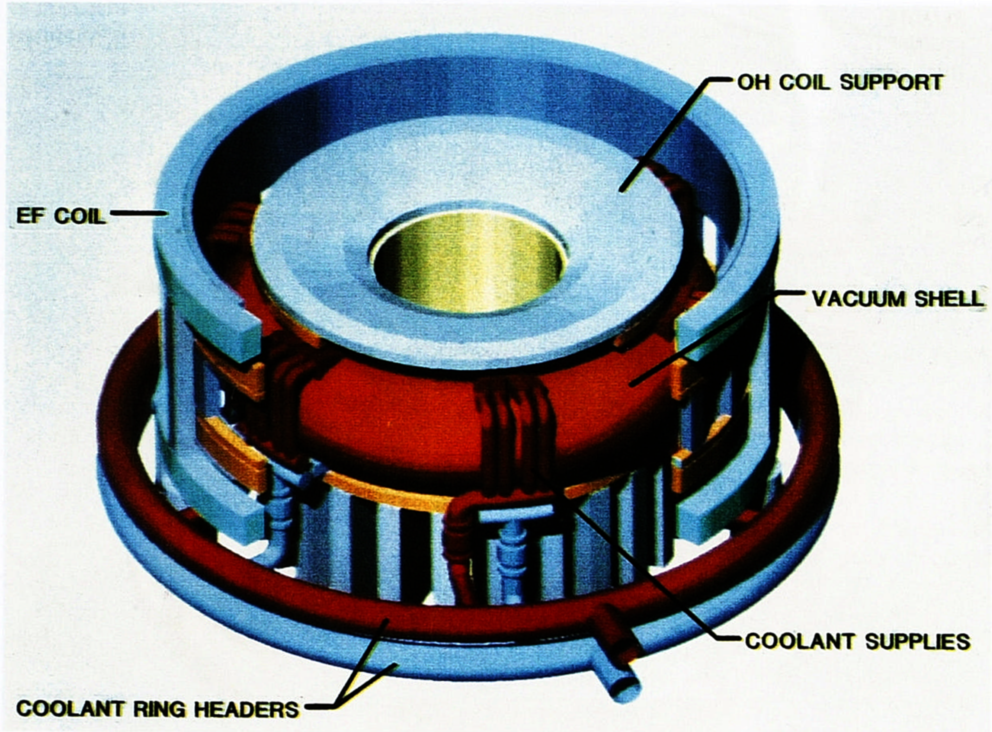
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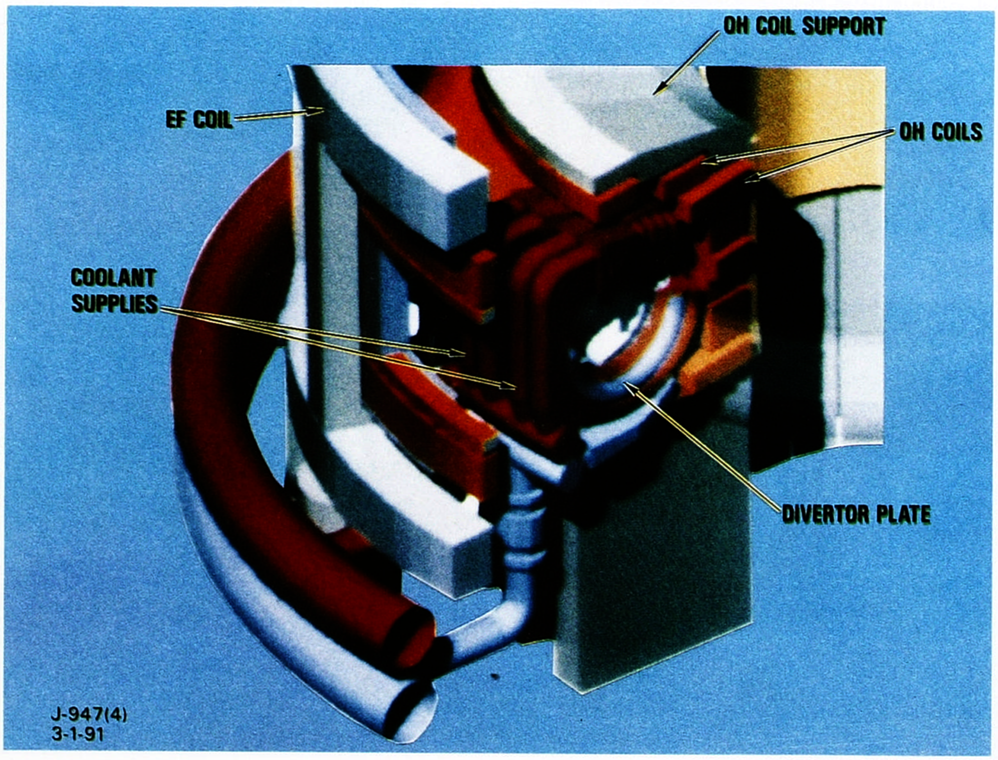
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coils are energized during the start-up by the OH-coil circuit. A pair of small EF "trim" coils are included to produce the exact vertical field needed during start-up. They are also utilized for equilibrium control during the burn and OFCD operation.

3. TITAN-I fusion power core

The TITAN-I fusion power core [3] (FPC) is a lithium, self-cooled design with a vanadium-alloy (V-3Ti-1Si) structural material. Magnetohydrodynamic (MHD) effects had precluded the use of liquid-metal coolants for high-heat-flux components in previous designs (mainly of tokamaks), but the magnetic field topology of the RFP is favorable for liquid-metal cooling. In the TITAN-I design, the first wall and blanket consist of single-pass, poloidal-flow loops aligned with the dominant, poloidal magnetic field. Other major features are: separation of the first-wall- and blanket-coolant circuits to allow a lower coolant-exit temperature from the first wall; and utilization of MHD turbulent-flow heat transfer at the first wall, which is made possible by the low magnetic-interaction parameter. The TITAN-I thermal-hydraulic design (Table 1) can accommodate up to 5 MW/m^2 of heat flux on the first wall with a reasonable MHD pressure drop, a high thermal-cycle efficiency, and a modest pumping power of about 45 MWe [6]. A molten-salt tritium-extraction technique is used.

A unique feature of the TITAN-I design is the use of the integrated-blanket-coil (IBC) concept [7,24]. The IBC concept utilizes the poloidally flowing lithium coolant of the blanket circuit as the electrical conductor for the divert or and toroidal-field coils. The IBC concept eliminates the need to shield the coils and allows direct access to the blanket and shield assemblies thereby facilitating the maintenance procedure.

The general arrangement of the TITAN-I FPC is illustrated in Figs. 2 and 3. The operational (maintenance and availability [11]), safety, and environmental issues [4,9] have been taken into account throughout the design. For example, the entire FPC is contained in a vacuum tank to facilitate the remote making and breaking of vacuum welds. All maintenance procedures would be performed by vertical lift of the components (the heaviest component weighs about 250 tonnes), which reduces the size of the expensive confinement building. The number of remote handling procedures is few and the movements are uncomplicated. All of the primary-coolant ring headers are located above the torus for easy access during maintenance. This arrangement also ensures that the coolant will remain in the torus in the event of a break in the primary piping. The most severe safety event will be a loss-of-flow accident (LOFA). The FPC and the primary-coolant loop are located in an inert-gas-filled (Ar) confinement building, which together with the blanket containers and the vacuum vessel form three barriers to prevent air influx to reduce the hazards of lithium fires and to provide protection for the public from radioactive materials. Lithium-drain tanks are provided for both the reactor vault and the vacuum tank to reduce passively the vulnerable inventory of lithium in the blanket.

A low-activation, low-after-heat vanadium alloy is used as the structural material throughout the FPC in order to minimize the peak temperature during a LOFA and to permit near-surface disposal of waste. The maximum temperature during a first-wall loss-of-coolant accident (LOCA) and system LOFA (the most severe accident postulated for TITAN-I) is 990°C. Lithium-fire accident scenarios and site-boundary dose calculations were performed to understand the potential release of radioactivity under major accident and routine release conditions. The safety analysis indicates that the liquid-metal-cooled TITAN-I design can be classified as passively safe, without reliance on any active safety systems [4]. Thus, a high Level of Safety Assurance [25,26] for the compact TITAN-I design is expected.

4. TITAN-II fusion power core

The TITAN-II FPC is a self-cooled, aqueous "loop-in-pool" design with a dissolved Li salt ($LiNO_3$ with 5 at.% lithium) as the breeder [8]. The structural material is 9-C ferritic steel [27], a reduced-activation, high-strength alloy (12Cr–0.3V–1W–6.5Mn–0.08C). The first-wall and blanket lobes are integrated and contain the pressurized coolant at 12 MPa. The structural load from the pressurized lobes is supported by an outer

Fig. 4. The TITAN-II fusion power core.

Fig. 5. Cutaway view of the TITAN-II fusion power core.

support shell that packs several lobes into a blanket module, as illustrated in Figs. 4 and 5, and forms 1/12 of the reactor torus. Three toroidal divertor chambers divide the reactor torus into three sectors, each containing four blanket modules. The coolant enters the lobes from the bottom, flows around the torus poloidally, and exits through the top plena. Subcooled-flow-boiling heat transfer is needed to cool the first wall. The blanket zone contains beryllium rods with 9-C ferritic-steel cladding as the neutron multiplier.

Different lithium compounds were considered as the breeding salt in the aqueous solution, and solubility, corrosion, and radiolysis effects in a fusion environment were evaluated. The $LiNO_3$ solution was selected as the reference breeding material because it has a pH value close to neutrality and can be much less corrosive. Furthermore, preliminary estimates of radiolytic yield indicate that the formation of an explosive gas mixture of hydrogen and oxygen may be avoidable for $LiNO_3$ because of the presence of nitrate ions. Account is taken of the thermophysical properties of the salt solution, which are significantly different from those of the pure water. The TITAN-II tritium-control and extraction system are, in principle, an extension of the technology developed by the Canadian CANDU fission-reactor program [28].

A very key feature of TITAN-II is that the FPC and the entire primary loop are submerged in a pool of low-temperature, low-pressure water. The basic sources of thermal energy after reactor shutdown are from the hot loop and the induced afterheat from the torus first-wall and blanket structures. The first-wall- and blanket-coolant channel configurations are designed to allow natural circulation to develop in the case of a LOFA. In the case of a major break in the primary-coolant pipes, the cold pool would absorb the thermal and afterheat energy from the hot loop. Calculations show that the pool remains at a temperature low enough to prevent the release of tritium or other radioactivity in the blanket-coolant system [9]. As such the TITAN-II design appears to achieve complete passive safety (Level 2 of Safety Assurance as defined in refs. [25,26]).

5. Implications for RFP physics research

The experimental and theoretical bases for RFPs have grown rapidly during the last few years years [16,23,29–32], but large degrees of extrapolations to TITAN-class reactors are still required. The degree of extrapolation is one to two orders of magnitude in plasma current and temperature and two to three

Table 2
Parameters of major RFP devices

Device	Major radius (m)	Minor radius (m)	Plasma current (MA)	Current density (MA/m^2)	Electron temperature (keV)	Average density (10^{20} m^{-3})	Poloidal β
TPE-1RM [a]	0.50	0.09	0.13	5.1	0.60	0.3	0.1
ETA-BETA-II [b]	0.65	0.125	0.15	3.0	0.08	1.0	0.1
HBTX1A [c]	0.80	0.26	0.32	1.5	0.10	0.2	0.05
OHTE/RFP [d]	1.24	0.20	0.50	4.5	0.4–0.6	0.5–3.0	0.1–0.2
ZT-40M [e]	1.14	0.20	0.44	3.5	0.3–0.5	0.4–0.9	0.1–0.2
RFX [f]	2.00	0.48	2.0	2.8	0.5–2.0	0.3–2.0	0.10
CPRF/ZTH [g]	2.40	0.40	4.0	8.0	0.5–5.0	0.3–5.0	0.10
FTF/RFP [h]	1.80	0.30	10.4	37.0	10.0–20.0	6.0–9.0	0.1–0.2
TITAN [i]	3.80	0.60	18.2	16.0	10.0–20.0	9.0	0.2

[a] Existing experiment at ETL, Japan [33,34].
[b] Existing experiment at Padova, Italy [35–37].
[c] Existing experiment at Culham, UK [38,39].
[d] Existing experiment at General Atomics, USA [40,41].
[e] Existing experiment at Los Alamos National Laboratory, USA [42,43].
[f] Existing experiment at Padova, Italy [44] (design goals).
[g] Planned experiment at Los Alamos National Laboratory, USA [44] (canceled).
[h] Conceptual neutron source, a Los Alamos National Laboratory study, USA [45].
[i] Conceptual reactor design, a UCLA-led multi-institutional study, USA.

orders of magnitude in energy confinement time (Table 2 and Fig. 6). However, the TITAN plasma density, poloidal β, and current density all are close to present-day experimental achievements. The next generation of RFP experiments [23,32] with hotter plasmas will extend the data base toward reactor-relevant regimes of operation (Fig. 6). The TITAN study has brought out and illuminated a number of key physics issues, some of which require greater attention from the RFP physics community.

The physics of confinement scaling, plasma transport, and the role of the conducting shell are already major efforts in RFP research. However, the TITAN study points to three other major issues. First, operating high-power-density fusion reactors with intensely radiating plasmas is crucial. Confirming that the global energy confinement time remains relatively unaffected while core-plasma radiation increases (a possible unique feature of RFPs) is extremely important. Second, the TITAN study has adopted the use of three "open-geometry" toroidal divertors as the impurity-control and particle-exhaust system. Even with an intensely radiative plasma, an array of poloidal pump-limiters would encounter serious erosion of the limiter blades (and possibly the first wall). The physics of toroidal-field divertors in RFPs, must be examined,

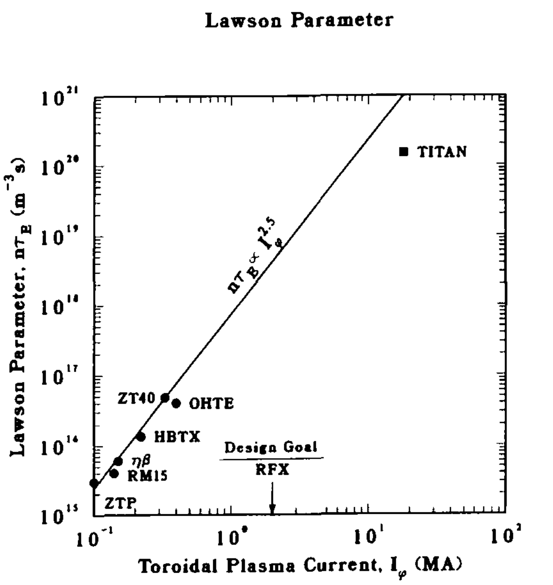

Fig. 6. Variation of the confinement parameter with plasma current with data from several experiments. These early data formed the basis of scaling relationships used in early studies of the RFP reactor [18].

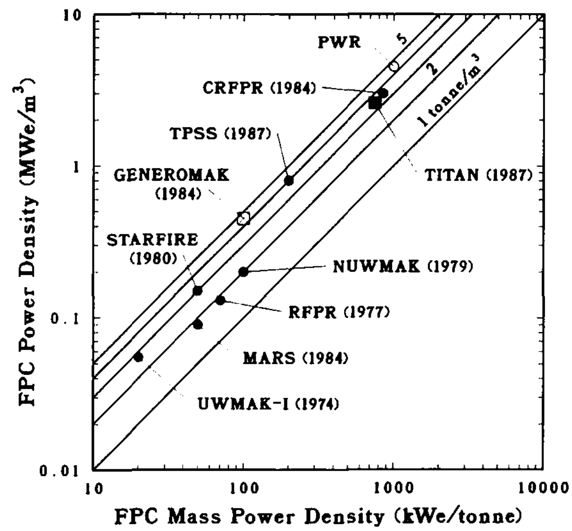

Fig. 7. The MPD and the FPC power density of several fusion-reactor designs, including TITAN and a fission PWR.

and the impact of the magnetic separatrix on RFP confinement must be studied. If toroidal divertors are consistent with confinement and stability in RFPs, then high-recycling divertors and the predicted high-density, low-temperature scrape-off layer must be also confirmed. Third, early work in the TITAN study convinced the team that high MPD, compact RFP reactors must operate at steady state. Current drive by magnetic-helicity injection utilizing the natural relaxation process in the RFP plasma is predicted to be efficient [19,20], but experiments on the OFCD are inconclusive. Testing the OFCD in higher temperature plasmas is required to validate this concept.

6. Conclusions

The TITAN research supports the technical feasibility of high-MPD RFP fusion reactors. The TITAN designs have an MPD value of about 800 kWe/tonne of FPC, approaching that of a pressurized-water fission reactor (PWR), as shown in Fig. 7. By contrast, earlier studies of tokamak and tandem-mirror reactors (such as STARFIRE [46] and MARS [47], respectively) had MPD values of around 50 kWe/tonne. Recent work suggests tokamaks may achieve values between 100 to 200 kWe/tonne [13]. The RFP has inherent characteristics that allow it to operate at very high MPDs [16]. Parametric studies show that such compact RFP reactors would include machines with neutron wall loading in the range 10–20 MW/m^2. Reactors in this "design window" are physically small, and a potential benefit of this "compactness" is improved economics. Also, the cost of the FPC for TITAN reactors is a small fraction of the overall estimated plant cost (< 10%), making the economics of the reactor less sensitive to changes in the plasma performance or unit costs for FPC components. Moreover, since the FPC is smaller and cheaper, a development program should cost less. The TITAN study further shows that, with proper choice of materials and FPC configuration, compact reactors can be made passively safe and, thus, the potential attractive safety and environmental features of fusion need not be sacrificed in compact reactors.

The compactness of the TITAN designs would reduce the FPC to a few small and relatively low-mass components, making toroidal segmentation unnecessary. Thus, a "single-piece" FPC maintenance procedure in which the first wall and blanket is removed and replaced as a single unit is possible. This unique approach permits the complete FPC to be made of a few factory-fabricated pieces, assembled on site into a single torus, and tested to full operational conditions before commitment to nuclear service. The low cost of the FPC means that a complete, "ready-for-operation" spare unit be can be kept on site for replacement in case of unscheduled events. All of these features are expected to improve the plant availability.

It must be emphasized, nevertheless, that in high-power-density designs such as TITAN, the in-vessel components (e.g., first wall and divertor plates) are subject to very high surface heat flux and that their design remains an engineering challenge. Also, the RFP plasma itself must operate in the manner outlined: with toroidal-field divertors, with a highly radiative core plasma, and at steady state. Future research will determine if, in fact, the physics and technology requirements of TITAN-class RFP reactors are achievable.

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