

The TITAN-I Reversed-Field-Pinch fusion-power-core design

Farrokh Najmabadi ^a, Clement P.C. Wong ^b, Steven P. Grotz ^a, Kenneth R. Schultz ^b, Edward T. Cheng ^{b,1}, Patrick I.H. Cooke ^{a,2}, Richard L. Creedon ^{b,3}, Nasr M. Ghoniem ^a, Robert A. Krakowski ^c, Mohammad Z. Hasan ^a, Rodger C. Martin ^{a,4}, James P. Blanchard ^{a,5}, Shahram Sharafat ^a, Don Steiner ^d, Dai-Kai Sze ^e, William P. Duggan ^{d,6} and George O. Orient ^{a,7}

^a *Institute of Plasma and Fusion Research, University of California, Los Angeles, CA 90024-1597, USA*

^b *General Atomics, San Diego, CA 92186, USA*

^c *Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*

^d *Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA*

^e *Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439, USA*

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 operational, safety, and environmental features of high mass-power-density (MPD) fusion-reactor systems.

Parametric system studies have been used to find cost-optimized designs. The design window for compact RFP reactors includes the range of 10–20 MW/m². The reactors are physically small, and a potential benefit of this “compactness” is improved economics. The TITAN study adopted 18 MW/m² in order to assess the technical feasibility and physics limits for such high-MPD reactors.

The TITAN-I design is a lithium self-cooled design with a vanadium-alloy (V–3Ti–1Si) structural material. The magnetic field topology of the RFP is favorable for liquid-metal cooling. The first wall and blanket consist of single pass poloidal-flow loops aligned with the dominant poloidal magnetic field. A unique feature of the TITAN-I design is the use of the integrated-blanket-coil (IBC) concept. The lithium coolant in the blanket circuit is also used as the electrical conductor of the toroidal-field and divertor coils. A “single-piece” FPC maintenance procedure is used, in which the first wall and blanket are removed and replaced by vertical lift of the components as a single unit. 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 installation in the reactor vault.

A low-activation, low-afterheat vanadium alloy is used as the structural material throughout the FPC in order to minimize the peak temperature during accidents and to permit near-surface disposal of waste. 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.

The results from the TITAN study support the technical feasibility, economic incentive, and operational attractiveness of compact, high-MPD RFP reactors. Many critical issues remain to be resolved, however. 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. Second, the physics of toroidal-field divertors in RFPs must be examined. Third current drive by magnetic-helicity injection must be verified. The key engineering issues for the TITAN I FPC have also been defined. Future research and development will be required to meet the physics and technology requirements that are necessary for the realization of the significant potential economic and operational benefits that are possible with TITAN-like RFP reactors.

Present addresses:

¹ TSI Research, Solana Beach, CA 92075, USA

² On assignment from Culham Laboratory, Abington, Oxfordshire, UK

³ Advanced Cryomagnetics, 7390 Trade Street, San Diego, CA 92121, USA

⁴ Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

⁵ University of Wisconsin, Fusion Technology Institute, Madison, WI 53706–1687, USA

⁶ Department of Mechanical Engineering, Manhattan College, Riverdale, NY 10471, USA

⁷ Rocketdyne Division of Rockwell International Corp., 6633 Canoga Ave., Canoga Park, CA 91303, USA.

1. Introduction

The TITAN research program is a multi-institutional [1] 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 [2–5] 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 [2] 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 RFP has inherent characteristics that allow it to operate at very high MPDs. The main confining field in an RFP is the poloidal field, which is generated by the large toroidal current flowing in the plasma. This results in a low field at the external magnet coils, a high plasma β , and a very high engineering β 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 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 [6] allow it to meet, and actually far exceed, the economic threshold MPD value of 100 kWe/tonne. The program, therefore, has chosen a neutron wall loading of 18 MW/m² as the reference case in order to quantify the issue of engineering practicality of operating at high MPDs. 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 a single-piece maintenance approach [7,8], in which all components are replaced as a single unit. In the TITAN designs, the entire reactor torus is replaced as a single unit during the annual scheduled maintenance. The single-piece maintenance procedure is expected to result in the shortest maintenance downtime because: (1) the number of connects and disconnects needed to replace components will be minimized, and (2) the replaced components are pretested before commitment to service.

A self-cooled, lithium-loop design with a vanadium-alloy structure was selected as the first design (TITAN-I) to be studied. The choice was based primarily on the capability to operate at high neutron wall load and high surface-heat flux.

The operating space of the TITAN compact RFP reactors has been examined using a comprehensive parametric systems model. Two key figures of merit, the cost of electricity (COE) and MPD, are displayed in Fig. 1 of the introduction by F. Najmabadi (see p. 71), 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/m². The MPD increases monotonically with the wall load. For designs with a neutron wall load larger than about 10 MW/m², single-piece FPC maintenance is feasible. The TITAN reactors have an MPD in excess of 500 kWe/tonne, improvement by a factor of 10 when 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 [4,5]. Therefore, the unit direct cost (UDC) is less sensitive to physics and technology uncertainties. The major parameters of the TITAN-I reactor are summarized in Table 1.

The TITAN-I RFP plasma operates at steady state using oscillating-field current drive (OFCD) [9,10] to maintain the 18 MA of plasma current. 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 [6,11,12] to operate with a highly radiative core plasma, deliberately doped with a trace amount of high-Z Xe impurities. The high-recycling divertor operates with high density and low temperature near the divertor target ($n_e = 10^{21} \text{ m}^{-3}$, $T_e = 5$

eV). The first-wall and divertor-plate erosion rate is negligibly small.

2. Configuration

The entire TITAN-I FPC operates inside a vacuum tank, which is made possible by the small physical size of the reactor (Fig. 1). During maintenance of the FPC, the weld at the lid of the vacuum tank must be cut and then re-welded after the maintenance is completed.

The TITAN-I vacuum tank also provides an additional safety barrier. The entire primary-coolant system is enclosed within the containment building, which is filled with argon to reduce the probability of a lithium fire in case of major rupture of coolant pipes. Drain banks are provided below the FPC (Fig. 1) to recover and contain any lithium spilled in the vacuum tank or the reactor building. The entire primary-coolant system

is located above the FPC in order to eliminate the possibility of a complete loss-of-coolant accident (see also Figs. 2 and 3 of the Introduction on p. 73).

The TITAN plasma is ohmically heated to ignition by using a set of normal-conducting ohmic-heating (OH) coils and a bipolar flux swing. An important safety-design guideline for TITAN-I allows no water inside the containment building and vacuum vessel in order to reduce the probability of lithium–water reactions. As a result, the OH coils are cooled by helium gas. A pair of relatively low-field, superconducting equilibrium-field (EF) coils produce the necessary vertical field, and a pair of small, copper EF trim coils provide the exact equilibrium during the start-up and OFCD cycles. The poloidal-field-coil arrangement allows access to the complete reactor torus by removing only the upper OH-coil set.

Another unique feature of the TITAN-I design is that the divertor and the toroidal-field (TF) coils are based on the integrated-blanket-coil (IBC) concept [13].

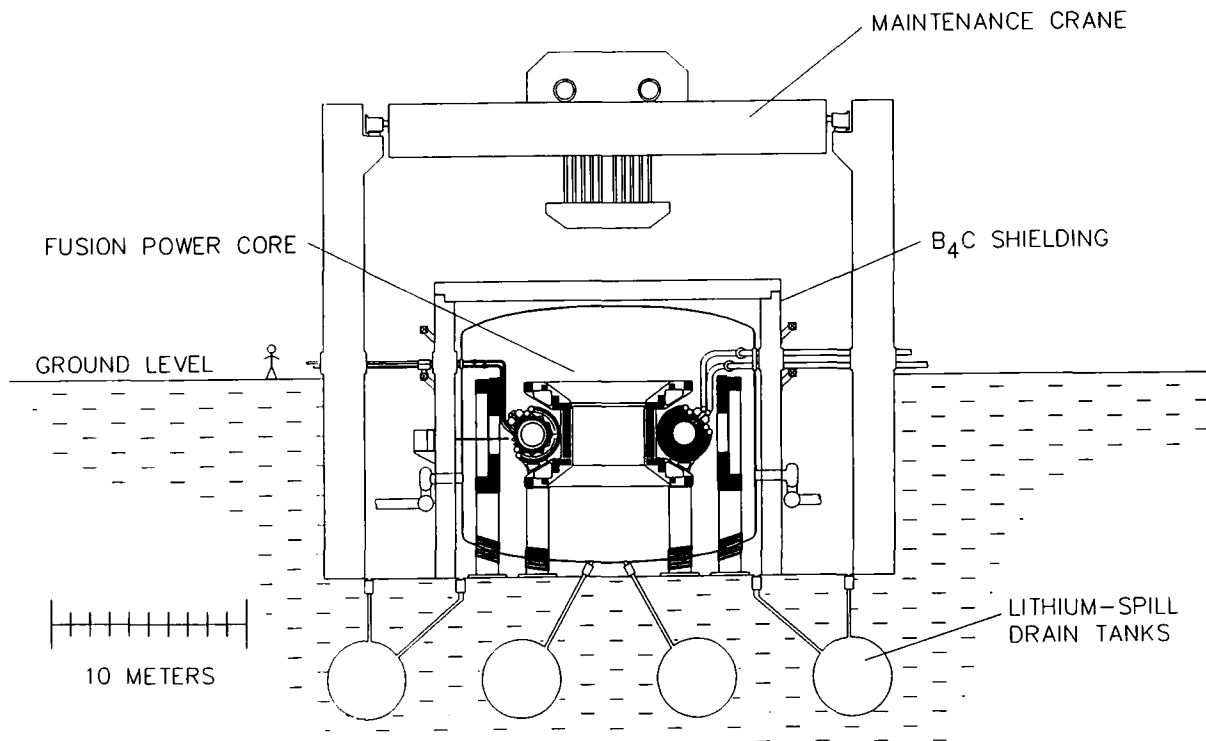


Fig. 1. Elevation view of the TITAN-I reactor building through the reactor centerline showing the reactor vault, the maintenance crane, and the vacuum tank.

Table 1
Operating parameters of TITAN-I fusion power core

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

The IBC concept utilizes the poloidally flowing lithium coolant of the blanket as the electrical conductor for the divertor and TF coils. Although lithium is about 20 times more resistive than copper, the low toroidal-field requirement of RFPs results in acceptable power requirements for TF and divertor coils of, respectively, 24 and 120 MW. The dominant magnetic field at the plasma edge in the RFP is poloidal. Since, the TITAN-I FPC is cooled by lithium, the coolant channels in the first wall and blanket are aligned with the poloidal field to minimize the induced MHD pressure drops.

The TITAN reactors operate with a highly radiative core plasma. The first wall intercepts the radiation heat flux of about 4.6 MW/m². The TITAN-I first wall is made of a bank of circular tubes that are 8 mm in diameter. The blanket and shield coolant channels are designed with the consideration of heat transfer, blanket energy multiplication, tritium breeding, and shielding requirements. The overall thickness of the blanket and shield is 75 cm. The 28-cm-wide IBC zone is located 1 cm behind the first wall and consists of 6 rows of tubular coolant channels with an inside diameter of 4.75 cm and a wall thickness of 2.5 mm. The 45-cm-thick hot shield is located 1 cm behind the IBC

and consists of 5 rows of square coolant channels with outer dimensions of 6 cm and 4 rows of rectangular channels with thick walls to increase the structure volume fraction in this zone.

The coolant flow in both first wall and blanket are single pass and in the poloidal direction. Double-pass poloidal flow, however, is used in the hot shield. Lithium flows in through the first three square channels of the hot shield, makes a 180° turn at the inboard side, and exits through the last two square channels and the rectangular channels of the hot shield. During the annual FPC maintenance, the top half of the shield will be removed so that the torus assembly (including the first-wall, IBC and divertor sections) can be replaced.

The lifetime of the TITAN-I reactor torus (including the first wall, blanket, and divertor modules) is estimated to be in the range of 15 to 18 MWy/m², requiring the replacement of the reactor torus on a yearly basis. The lifetime of the hot shield is estimated to be five years.

3. Materials

When compared with iron-based alloys, vanadium-base alloys exhibit better physical, mechanical, and nuclear properties [14,15]. The high melting temperature of vanadium alloys ($T_m = 1890^\circ\text{C}$), the higher ultimate tensile strength ($\sigma_u \sim 600$ MPa at 600°C), the lower expansion coefficient, and the slightly higher thermal conductivity of vanadiumbase alloys are reflected in the heat load capability.

The vanadium alloy V-3Ti-1Si was chosen as the structural material for TITAN-I, primarily because of its irradiation behavior. Irradiation hardening and helium and hydrogen embrittlement of V-3Ti-1Si are expected to set an upper lifetime limit of approximately 18 MWy/m² for the TITAN-I first wall. Irradiation-induced swelling of the V-3Ti-1Si alloy would be negligible for the lifetime of the TITAN-I first wall. From the limited creep data [16], it appears that V-3Ti-1Si will be able to operate satisfactorily at elevated temperatures (700°C).

Compatibility data of the vanadium-base alloys with lithium coolant indicate the possibility of a self-limiting corrosion rate on V-3Ti-1Si because of the formation of complex vanadium-titanium-nitride surface layers. The effects of a bimetallic loop containing liquid lithium were also investigated. Low-carbon, titanium-stabilized ferritic steel exhibits good resistance against lithium corrosion.

In the TITAN-I design, the liquid-lithium coolant flows at a high velocity (21 m/s) in the first-wall channels. A literature search regarding erosion by liquid lithium showed that this issue has not been investigated in any detail, specifically for vanadium alloys. From a very limited set of data on erosion of refractory metals by high-velocity liquid lithium and from water-steel experience, it seems that a lithium velocity of 20 to 25 m/s should not introduce unacceptable erosion rates.

In the TITAN-I reactor, electrically insulating materials are not used in direct contact with the coolant; therefore coolant compatibility is not a major issue in selecting an insulating material. The selection criteria is based primarily on satisfying minimum irradiation-induced swelling, retention of strength, and minimum radiation-induced conductivity. Spinel ($MgAl_2O_4$) has been chosen as the primary electrical insulating material for the TITAN-I design, based on excellent resistance to radiation-induced swelling and retention of strength. A phenomenological swelling equation was developed as a function of temperature and damage dose, and it shows that operating spinel below 150°C ensures low swelling rates (< 5%).

4. Neutronics

The neutronics design of the blanket and shield for the TITAN reactors is unique because of the use of normal-conducting coils in the toroidal-field, divertor, and ohmic heating (OH) magnets. The neutron-fluence limit of the TITAN-I OH magnets is set by the spinel-insulator lifetime and is 3 to 4 orders of magnitude larger than that of a superconductor magnet (1×10^{23} n/m²) [17]. This implies a 0.6 to 0.8 m reduction in the shielding space and helps to maintain the compactness of the FPC design.

Neutronics calculations were performed on a 1-D blanket and shield model in a cylindrical geometry about the center of the poloidal cross section of the plasma. The neutron and gamma-ray transport code, ANISN [18], is used with the cross-section library ENDF/B-V-based MATXS5, processed with the NJOY system [19].

Scoping calculations were performed for several combinations of blanket and shield thickness with varying amount of structure and different levels of ⁶Li enrichment in the lithium coolant. The neutronics scoping studies resulted in the reference blanket and shield design of the TITAN-I illustrated in Fig. 2. The neutronics performance is given in Table 2. The maxi-

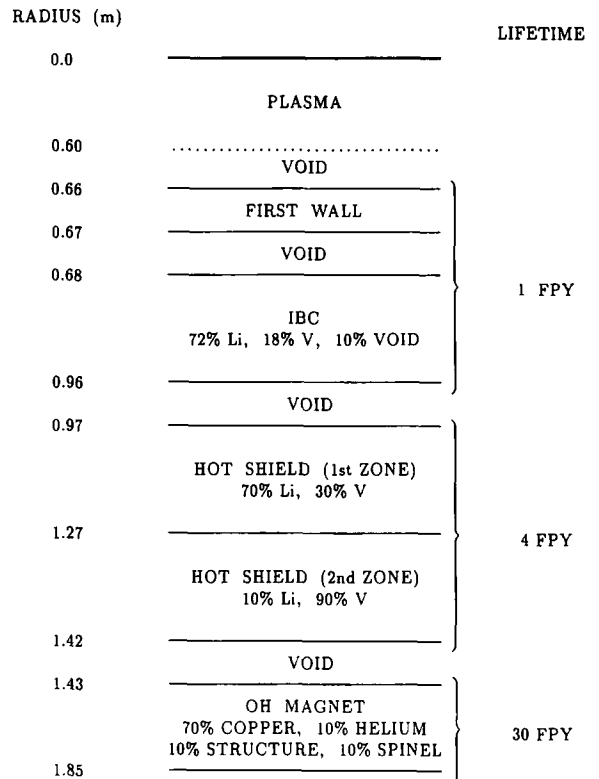


Fig. 2. Schematic of the blanket and shield for the TITAN-I reference design.

Table 2
Nuclear performance of the TITAN-I reference design ^(a)

• ⁶ Li enrichment	30 %		
• Tritium-breeding ratio:			
⁶ Li (n, α)	1.084		
⁷ Li (n, n', α)	0.247		
TOTAL	1.33		
• Blanket energy multiplication, M	1.14		
• Nuclear heating (MeV per DT neutron):			
Component	Neutron	Gamma ray	Sum
First wall	0.341	0.183	0.524
Blanket	7.382	2.603	9.985
Shield (1st zone)	3.148	1.595	4.743
Shield (2nd zone)	0.235	0.560	0.795
TOTAL	11.106	4.941	16.047
OH coils	0.038	0.438	0.476

^(a) From 1-D ANISN calculations.

imum fast-neutron fluence at the OH magnet after 30 fullpower years (FPYs) of operation is substantially lower than the estimated lifetime limit of the spinel insulator.

The final design parameters were verified by a set of 3-D neutronics calculations with the Monte Carlo code, MCNP [20], taking into account the toroidal geometry and the divertor modules. The tritium-breeding ratio for the 3-D model of the reference design is 1.18, and the maximum fast-neutron fluence at the OH magnet is well below the assumed lifetime limit for the spinel insulator.

5. Thermal and structural design

The TITAN-I FPC is cooled by liquid lithium. One of the issues for liquid-metal coolants in fusion reactors is the MHD-induced pressure drop. In an RFP fusion reactor such as TITAN, the toroidal magnetic field at the first wall is small; thus the MHD pressure drop can be kept low by alignment of the coolant channels primarily in the poloidal direction.

The TITAN designs operate with a highly radiative core plasma, in order to distribute the surface heat load uniformly on the first wall (4.6 MW/m^2) and to keep the heat load on the divertor target plates at a manageable level. Cooling the high-heat-flux components, such as the first wall and divertor target plates, represents one of the critical engineering aspects of compact fusion reactors. The use of a highly radiative core plasma is central to the solution to this problem. The main thermal-hydraulic design features of the TITAN-I FPC are:

- (1) First-wall sputtering is almost negligible as a result of the operation with a high-recycling divertor.
- (2) Small-diameter, thin-walled, circular coolant tubes are used for the first wall.
- (3) First-wall- and blanket-coolant circuits are separated.
- (4) Coolant channels are aligned with the dominant, poloidal magnetic field.
- (5) Turbulent-flow heat transfer is used to remove the high heat flux on the first wall.

The magnetic field, generally, tends to suppress turbulence in the flow of an electrically conducting fluid. A few studies on the turbulent heat transfer in liquid metals in the presence of a magnetic field [21–23] are available. The MHD pressure drops were calculated by various correlations appropriate for the TITAN-I design.

First Wall & Blanket Design Window

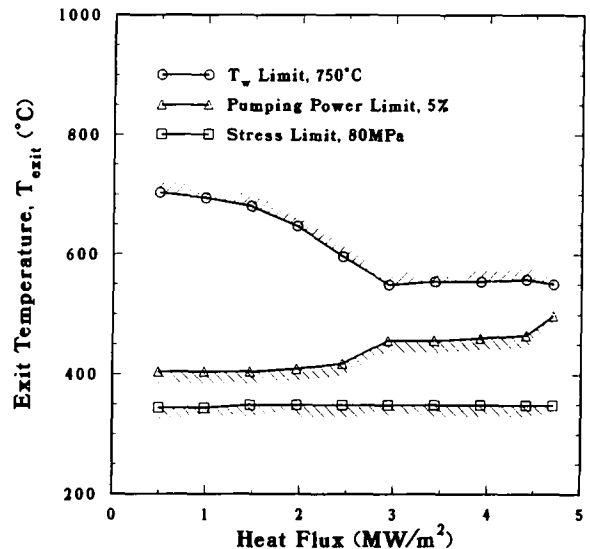


Fig. 3. The thermal-hydraulic design window for the TITAN-I FPC.

In order to complete the thermal-hydraulic design, pressure and thermal stresses in the FPC coolant channels were estimated by 1-D equations for a thick-walled tube. Two-dimensional thermomechanical analyses of the TITAN-I FPC were also performed using the finite-element code, ANSYS [24], which verified the 1-D analysis.

A thermal-hydraulic design window for compact liquid-lithium-cooled RFP reactors was found based on certain design constraints such as the maximum allowable temperature of the structure (750°C), the maximum allowable pressure and thermal stresses in the structure (respectively, 108 and 300 MPa), and the maximum allowed pumping power (5% of plant output). Fig. 3 illustrates the thermal-hydraulic design window for the TITAN-I first wall and shows that a design with a radiation heat flux on the first wall of 4.9 MW/m^2 is possible (corresponding to 20 MW/m^2 of neutron wall load at 95% total radiation fraction). The sudden change in the slope of the top curve in Fig. 3 is caused by the change from laminar to turbulent flow. The flow in the blanket and shield is always laminar.

The main results of the thermal-hydraulic analysis of the TITAN-I first wall are given in Table 3. The maximum pressure drops in the first-wall coolant tube and in the divertor coolant circuits are, respectively, 10

MPa and 12 MPa. The first-wall and divertor coolants are supplied from the same circuit with a delivery pressure of 12 MPa. The supply pressure of the blanket coolant pump is 3 MPa.

6. Magnet engineering

Three types of magnets are used in the TITAN-I design. The ohmic-heating (OH) and the equilibrium-field (EF) trim coils are normal-conducting with copper alloy as the conductor, spinel as the insulator, and gaseous helium as the coolant. The main EF coils, which are made of NbTi conductor and steel structural material, are superconducting.

The divertor and the toroidal-field (TF) coils of the TITAN-I design are based on the integrated-blanket-coil (IBC) concept [13]. The IBC as applied to TITAN-I also acts as the toroidal-field driver coil for the oscillating-field current-drive system. The TF coils of TITAN-I oscillate at 25 Hz with currents ranging between 30% and 170% of the mean steady-state value of 7.0 MA-turns. The PF coils also oscillate at 25 Hz. It is also necessary to oscillate the divertor coils to maintain the plasma separatrix at the proper location.

The IBC design encounters several critical engineering issues: (1) steady-state and oscillating power-supply requirements for low-voltage, high-current coils; (2) time-varying forces caused by the OFCD cycles; (3) integration of the primary heat-transport system with the electrical systems; (4) sufficient insulation to stand off induced voltages; and (5) suitable time constants for various components to permit the coil currents to oscillate at 25 Hz. Heat removal is not an issue for the IBC because the joule heating is produced directly in the primary coolant.

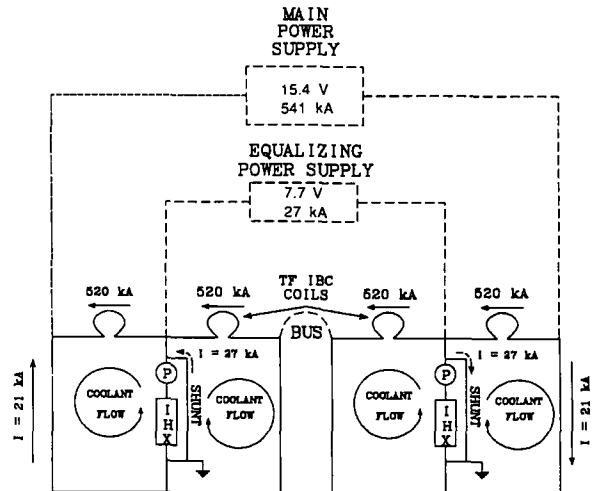


Fig. 4. Schematic of the electrical and hydraulic layout of TITAN-I TF IBCs.

late at 25 Hz. Heat removal is not an issue for the IBC because the joule heating is produced directly in the primary coolant.

Design of the power supplies is one of the critical issues for IBC. The low number of electrical turns available (12 for the TITAN-I design) results in low-voltage, high-current coils (3.85 V, 520 kA per coil). Power supplies rated for such conditions would be expensive and would exhibit high internal-power losses. Connecting all 12 IBCs of TITAN-I in series would raise the voltage of the power supply to a more manageable value. However, the IBC approach requires that the electrical and hydraulic systems be physically connected, and that the intermediate heat exchangers (IHxs) and coolant pumps be grounded (i.e., no electric current flowing through the IHxs and pumps).

Fig. 4 illustrates the electrical and hydraulic layout of the TITAN-I IBC system. The TITAN-I FPC comprises three sectors, which are connected to each other through the divertor modules. The four IBCs in each sector are electrically connected in series, which allows a better match of current and voltage for the power supply (15.4 V, 541 kA). This circuit, however, requires two IHxs per sector for the IBC cooling circuit. Figure 4 shows that, because of the series connection of the IBCs and grounding of the pumps and heat exchangers, a leakage current will flow through the cold and hot legs, necessitating a small balancing power supply to accompany each main power supply. The load on

Table 3
Thermal-hydraulic design of TITAN-I first wall

Pipe outer diameter, b	10.5 mm
Pipe inner diameter, a	8.0 mm
Wall thickness, t	1.25 mm
Erosion allowance	0.25 mm
Coolant inlet temperature, T_{in}	320°C
Coolant exit temperature, $T_{ex,FW}$	440°C
Maximum wall temperature, $T_{w,Max}$	747°C
Maximum primary stress	50 MPa
Maximum secondary stress	288 MPa
Coolant flow velocity, U	21.6 m/s
Pressure drop, Δp	10 MPa
Total pumping power ^(a)	37.7 MW

^(a) A pump efficiency of 90% is assumed.

each balancing power supply (7.7 V and 27 kA) is much smaller than that of the main power supply (15.4 V and 541 kA) and leaks through the cold legs to ground.

The impurity-control system of the TITAN-I design comprises three toroidal-field divertors. Each divertor consists of one nulling coil and two flanking coils to produce the local effects necessary for field nulling. A pair of trim coils is added to each divertor in order to localize the toroidal-field ripple. The joule losses in the divertor IBCs (three divertors) are 117 MW with additional 3.5-MW losses in the hot legs.

Because of the large impedance of the toroidal-field circuit during the OFCD cycles (about 0.1 m Ω for each TF coil), the oscillating voltage on each TF coil (\sim 50 V) is much larger than the steady-state value (\sim 3.8 V). The joule losses in the TF coils during the OFCD cycle are estimated to be 25.6 MW for the steady-state portion and 16 MW for the oscillating voltages. It is necessary to oscillate the divertor coils during the OFCD cycle to maintain the plasma separatrix at the proper location. The oscillating losses in the divertor IBCs are estimated at 26 MW in the coils and 0.8 MW in the hot and cold legs.

7. Power cycle

The TITAN-I first wall and blanket have separate coolant circuits in order to handle the high surface-heat flux on the first wall. The first-wall coolant has a much lower exit temperature (440°C) than the blanket and shield coolant (700°C). The divertor coolant also has a different exit temperature (540°C). The inlet temperatures to all three circuits are kept the same. The first-wall and divertor coolants are mixed at exit, resulting in a temperature of 442°C.

The TITAN-I reference design uses two separate power cycles: one for the first-wall and divertor stream and the other for the IBC and shield stream. Each of these two power cycles has a separate IHX, steam generators, and turbine-generator set. The TITAN-I FPC consists of three toroidal sectors. One IHX and one steam generator are required per sector for the first-wall and divertor coolant stream. The steam produced in these three steam generators is mixed and fed to a single turbine-generator set. For the IBC and shield stream, two IHXs are used per sector. The secondary coolants of each pair of these heat exchangers are mixed and fed to one steam generator (per sector). The steam from all three steam generators is mixed and fed to a single turbine-generator set.

The power cycle analysis is performed by the computer code PRESTO [25]. The first-wall and divertor power cycle is a superheat Rankine cycle with four stages of feedwater heating. The total thermal power is 765 MW and the gross thermal efficiency is 37.0%. The IBC and shield power cycle is a superheat Rankine cycle with two reheat stages and seven stages of feedwater heating. The total thermal power in this cycle is 2170 MW, and the gross thermal efficiency of this cycle is 46.5%. The overall gross thermal efficiency for the TITAN-I design is 44%.

8. Divertor engineering

The design of the impurity-control system for a high-power-density device can be particularly challenging. The final TITAN-I divertor design is the result of extensive iterations between edge-plasma analysis, magnetic design, thermal-hydraulic and structural analysis, and neutronics.

A summary of the results of the edge-plasma modeling is given in Table 4. Injection of a trace amount of a high- Z material (xenon) into the plasma causes 95% of the steady-state heating power to be radiated to the first wall and divertor plate. This reduces the charged particle power that is deposited on the divertor target by the plasma to an acceptably low level. Preliminary experimental results [11,12] suggest that β -limited RFP plasmas can withstand a high fraction of power radiated without seriously affecting the global confinement. The radiative cooling also reduces the electron temperature at the first wall and divertor target (also assisted by recycling) which, in turn, reduces the sputtering and erosion problems.

Table 4
Summary of TITAN-I edge-plasma conditions

Number of divertors	3
Scrape-off layer thickness	6 cm
Peak edge density	$1.7 \times 10^{20} \text{ m}^{-3}$
Peak edge ion temperature	380 eV
Peak edge electron temperature	220 eV
Plasma temperature at first wall	1.7 eV
Peak divertor density	$6 \times 10^{21} \text{ m}^{-3}$
Peak divertor plasma temperature	4.5 eV
Divertor recycling coefficient	0.995
Throughput of DT	$6.7 \times 10^{21} \text{ s}^{-1}$
Throughput of He	$8.2 \times 10^{20} \text{ s}^{-1}$
Vacuum tank pressure	20 mtorr

A tungsten-rhenium alloy (W-26Re) is used for the plasma-facing surface. A bank of lithium-cooled, vanadium-alloy coolant tubes removes the heat deposited on the target. These tubes are separated from the W-26Re armor by a thin, electrically insulating layer of spinel to avoid an excessive MHD pressure drop.

TITAN-I uses toroidal-field divertors to minimize the perturbation to the global magnetic configuration (the toroidal field is the minority field in RFPs) and to minimize the coil currents and stresses. The TITAN divertor target is located close to the null point to take advantage of the flux expansion and thereby reduce the heat loading. The high plasma density in front of the divertor target ensures that the neutral particles emit-

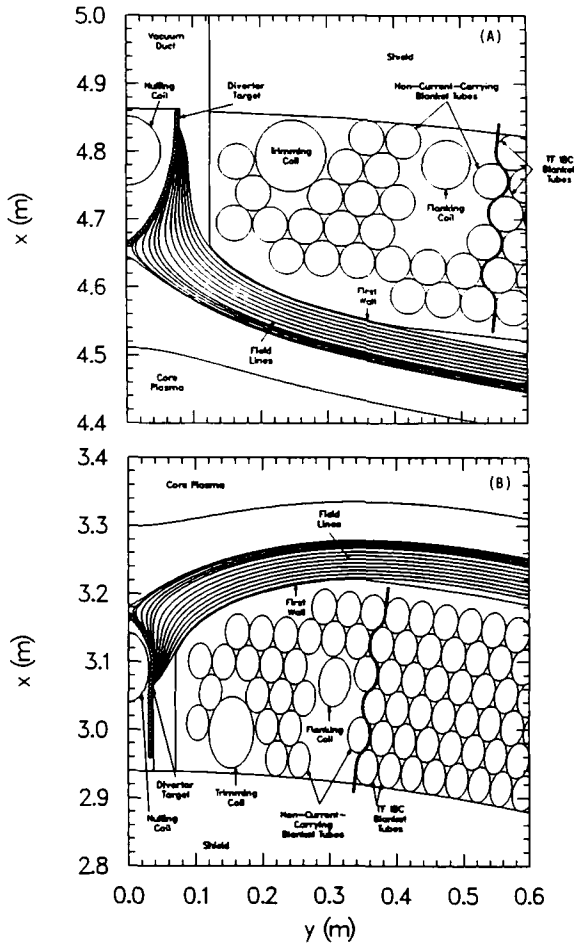


Fig. 5. Outboard (A) and inboard (B) equatorial-plane views of the divertor region for TITAN-I.

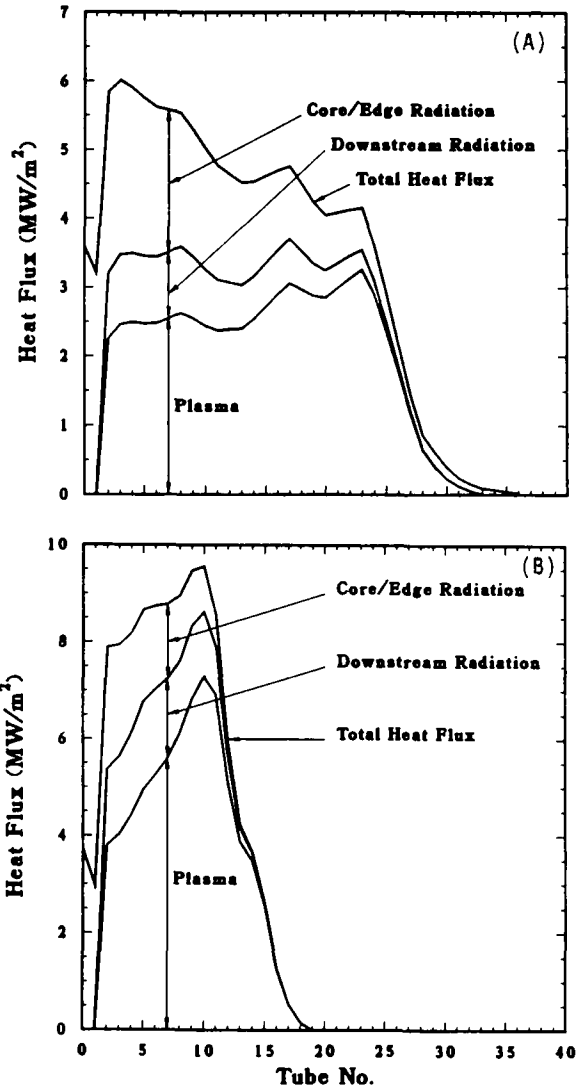


Fig. 6. Heat flux distribution on outboard (A) and inboard (B) sections of divertor target. Coolant tubes are numbered from the apex or symmetry point of the target between the nulling coil and the core plasma.

ted from the surface have a short mean free path; a negligible fraction of these neutral particles enter the core plasma.

The design includes three divertor modules, located 120° apart in the toroidal direction (Fig. 5). The magnetic field lines are diverted onto the divertor plate using a nulling coil and two flanking coils. A pair of trim coils is also required to control the toroidal-field

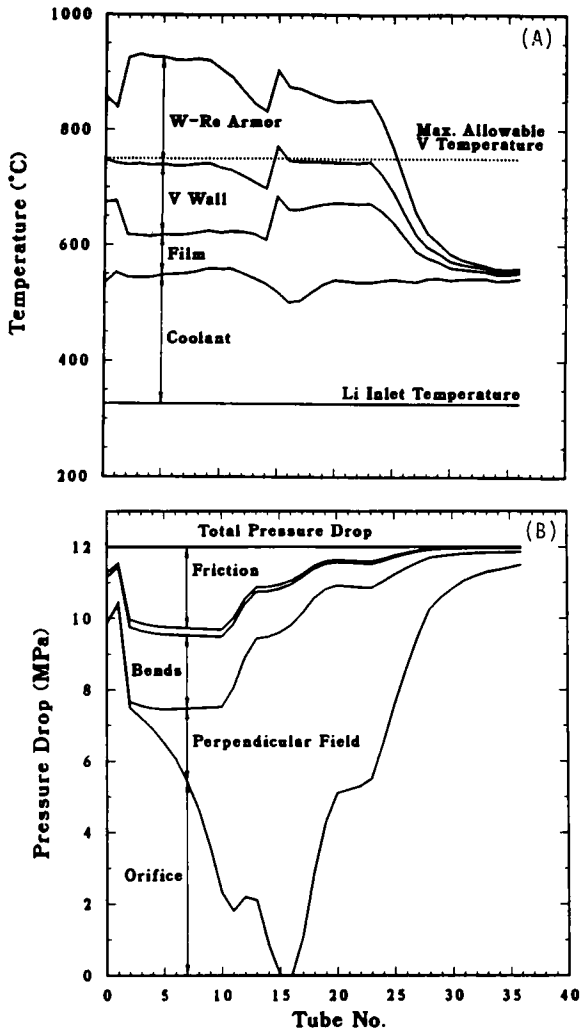


Fig. 7. Coolant and structural temperatures at the coolant outlet (A) and components of the coolant pressure drop (B) for coolant tubes in the divertor target. Coolant tubes are numbered from the apex or symmetry point of the target between the nulling coil and the core plasma.

ripple. Careful shaping of the divertor target is required to maintain the heat flux at acceptable levels at all points on the plate. Figure 6 shows the various components of the surface heat flux.

The temperature distribution of the target plate coolant and structure is shown in Fig. 7. The maximum temperature of the vanadium-alloy tubes does not exceed 750°C. The maximum temperature of the W-26Re armor is about 930°C, at which level the alloy retains

high strength and the thermal stresses are within allowable levels.

A total pressure drop of 12 MPa was used for the divertor-coolant circuit. The maximum-allowable coolant velocity was set at 25 m/s to avoid physical erosion. Figure 7 also shows the components of the pressure drop in the divertor-coolant tubes. Flow orificing is used to tailor the coolant velocity distribution so as to maintain an outlet temperature that is approximately constant across the plate.

The vacuum system is a large vacuum tank encompassing the entire torus and connected by a duct at each of the three divertor locations. Lubricant-free, magnetic-suspension-bearing turbo-molecular pumps are used to avoid tritium contamination of oil lubricants.

9. Tritium systems

In the TITAN design, separation of the D and T of the plasma exhaust is not required. Therefore, only about 1% of the plasma exhaust will be required to pass through the cryogenic distillation system to separate protium generated by the DD reaction. A redundant unit is used, which can significantly improve the reliability of the system and allow the reactor tritium storage to be reduced.

A molten-salt recovery process [26], in which the liquid lithium and a molten salt are in contact, is selected for tritium recovery from the lithium blanket,

Table 5
Tritium inventories in TITAN-I reactor

Unit	Tritium inventory (g)
Storage	1,100
Primary-coolant loop	212
Secondary-coolant loop	300
Molten-salt extraction	10
Fuel processing	20
First wall:	
typical case	0.72
excessive PDP	4.53
Integrated blanket coil	2.20
Hot shield, zone 1	0.14
Hot shield, zone 2	0.25
Divertor shield	0.08
Divertor	< 0.01
Out-of-blanket piping	≪ 0.01
Total TITAN-I inventory	1,650

and LiH is preferentially distributed to the salt phase. The salt is then electrolyzed to yield hydrogen. The molten salt recovery process has been demonstrated on a laboratory scale to recover tritium from lithium down to 1 wppm. Therefore, the tritium inventory in the blanket would be moderate.

For the TITAN-I design, lithium is used as the intermediate coolant. A unique advantage of using lithium is that the tritium partial pressure is very low. For a tritium concentration of 1 wppm, the tritium partial pressure is only 10^{-7} Pa. With such low tritium partial pressure, tritium containment is not a problem. The tritium inventories in TITAN-I components are shown in Table 5. The TITAN-I tritium inventory (1,650 g) and leakage rate (7 Ci/d) are very reasonable.

A potential problem facing TITAN-I is the plasma-driven permeation (PDP) of lowenergy tritons through the permeable vanadium-alloy first wall. Experiments are needed to determine the extent of PDP and the sputtering rate of the first-wall structure at low edge-plasma temperatures. Because tungsten is very resistant to permeation, PDP through the divertor plate is not a concern.

10. Safety design

Strong emphasis has been given to safety engineering in the TITAN study. The safety design objectives of the TITAN-I design are: (1) to satisfy all safety-design criteria as specified by the U.S. Nuclear Regulatory Commission on accidental releases, occupational doses, and routine effluents; and (2) to aim for the best possible level of passive safety assurance.

The key safety features of the lithium self-cooled TITAN-I design are:

- The selection of a low-afterheat structural material, V-3Ti-1Si;
- The selection of a relatively high ^6Li enrichment (30%) to aid in further reducing afterheat and radioactive wastes;
- The use of three enclosures to separate the lithium and air: blanket tubes, vacuum vessel, and the containment building, which is filled with argon cover gas;
- Locating all coolant piping connections at the top of the torus to prevent a complete loss of coolant in the FPC in case of a pipe break;
- The use of lithium-drain tanks to reduce the vulnerable lithium inventory should a pipe break occur;

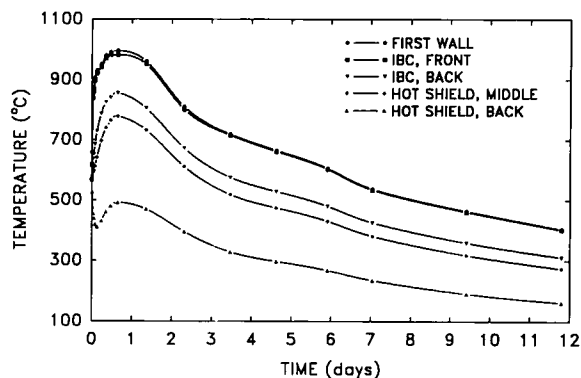


Fig. 8. The thermal response of the TITAN-I FPC to a complete LOFA as a function of time after the initiation of the accident.

- The use of steel liner to cover the containment-building floor to minimize the probability of lithium-concrete reaction;
- Excluding water from the containment building and vacuum vessel to prevent the possibility of lithium-water reaction.

Two of the major accidents postulated for the fusion power core are the loss-of-flow accident (LOFA) and the loss-of-coolant accident (LOCA). Thermal responses of the TITAN-I FPC to these accidents are modeled using a finite-element heat-conduction code, TACO2D [27]. Figure 8 shows the resulting temperatures during a LOFA. At 12.8 hours after the initiation of the accident, the first wall reaches its peak temperature of 990°C, which is below the recrystallization temperature of the V-3Ti-1Si alloy, and well below $\sim 1300^\circ\text{C}$, the onset of volatilization of radioactive products (CaO, SrO) in the vanadium alloy. The heat capacity of the static lithium accounts for the moderate temperature excursion. No natural convection of the coolant is assumed. If natural convection develops, the temperature excursions would be considerably smaller than those predicted by Figure 8.

For the materials and loadings expected in the TITAN-I first wall during a LOFA, the thermal stresses have a negligible influence on the rupture time relative to the pressure stresses. Since the coolant pressure is lost during off-normal conditions, creep-rupture would not occur even if the structure was kept at elevated temperatures (1000°C) for a prolonged period of time - a LOFA would not lead to a LOCA.

Higher afterheat is expected in the tungsten plate of the divertor. During a LOFA, the peak temperature in the divertor vanadium cooling tube is 1117°C , close to

Table 6
Maximum concentration levels of impurities in TITAN-I reactor components to qualify as Class-C waste

Element	Major nuclide (activity limit) ^(a)	Components			Nominal level
		FW & blanket (1 FPY) ^(b)	Hot shield (5 FPY) ^(b)	OH magnets (30 FPY) ^(b)	
Nb (appm)	⁹⁴ Nb (0.2 Ci/m ³)	5.0	1.4	0.5	4.0
Mo (appm)	⁹⁹ Tc (0.2 Ci/m ³)	65.0	100.0	90.0	1.0
	⁹⁴ Nb (0.2 Ci/m ³)				
Ag (appm)	^{108m} Ag (3 Ci/m ³)	1.3	1.5	0.7	1.0 ^(c)
Tb (appm)	¹⁵⁸ Tb (4 Ci/m ³)	0.4	0.6	7.0	5.0 ^(c)
Ir (appm)	^{192m} Ir (2 Ci/m ³)	0.1	0.1	0.02	5.0 ^(c)
W%	^{186m} Re (9 Ci/m ³)	5%	9%	100%	0.89%

^(a) From ref. [30].

^(b) Based on operation at 18 MW/m² of neutron wall loading.

^(c) Estimate.

recrystallization temperature of the V-3Ti-1Si. This may cause a shortening of the lifetime of the divertor modules, but failure that would lead to a LOCA is unlikely.

In the event of major primary-pipe breaks and simultaneous failure of the containment building and vacuum vessel, air could enter the vacuum chamber and start a lithium fire. TITAN-I is configured (1) to ensure that a lithium fire would be a low probability event, and (2) to minimize the consequences of a lithium fire, should it occur. In order to reduce the probability of lithium fires, three barriers (primary-coolant pipes, the vacuum tank, and the containment building) exist between the primary-coolant lithium and air. The containment building is also filled with argon cover gas. In order to reduce the consequences of a lithium spill, two sets of lithium-drain tanks are provided to drain the maximum amount of lithium in less than 30 seconds.

For the perceived worst-case accident condition of a lithium fire with a breach of all barriers and no argon cover gas, the maximum combustion-zone temperature is found to be less than 1000°C. The tritium release in this case would be about 60 Ci, which is quite acceptable under this worst-case accident scenario. Of critical concern in the lithium-fire scenario is the formation and release of vanadium oxide (V₂O₅). Further measurement of vanadium-oxide formation and its vapor pressure with temperature, and the calculation of potential releases to the public should be performed.

Based on the analyses summarized above, TITAN-I does not need to rely on any active safety systems to protect the public. A LOFA will cause no radioactive release and will not lead to a more serious LOCA. A complete LOCA from credible events is not possible.

Only the assurance of coolant-piping and vacuum-vessel integrity is necessary to protect the public. The TITAN-I design, therefore, meets the definition of level 3 of safety assurance, "small-scale passive safety assurance" [28,29]. Pending information on the vanadium-oxide formation and release from the TITAN-I vacuum chamber under the lithium-fire accident scenario, the qualification of TITAN-I as a level-2 of safety assurance design, "large-scale passive safety assurance," may also be possible.

11. Waste disposal

The neutron fluxes calculated for the reference TITAN-I reactor were used as input to the activation calculation code, REAC [30], to determine allowable concentrations of alloying and impurity elements in TITAN-I FPC components. The key features in achieving Class-C waste disposal [31] are materials selection and the control of impurity elements.

The materials selected for the TITAN-I FPC are the vanadium alloy (V-3Ti-1Si) and lithium. The main alloying elements of V-3Ti-1Si do not produce long-lived radionuclides with activity levels exceeding the limits for Class-C disposal (no limit on the concentration of vanadium and titanium and 23% allowable concentration of silicon, which is much larger than the 1% content of Si in V-3Ti-1Si). The allowable concentrations of various impurities in the vanadium structural material of the TITAN-I reactor are listed in Table 6. Also shown are the nominal levels that are expected to be found in the V-3Ti-1Si alloy (estimated from ref. [15]). Some of these impurity elements, mainly niobium and possibly silver, terbium, and irid-

Table 7
Summary of TITAN-I reactor materials and related waste quantities for Class-C waste disposal ^(a)

Component	Material	Lifetime (FPY)	Volume (m ³)	Weight (tonnes)	Annual replacement mass (tonnes/FPY)
First wall	V-3Ti-1Si	1	0.4	2.5	2.5
Blanket (IBC)	V-3Ti-1Si	1	6.4	39.2	39.2
Shield (zone 1)	V-3Ti-1Si	5	15.5	95.6	19.1
Shield (zone 2)	V-3Ti-1Si	5	28.0	172.0	34.4
OH coils	Modified steel	30	3.8	34.0	1.1
	Copper		26.6	239.0	8.0
	Spinel		3.8	15.2	0.5
	TOTAL		34.2	289.2	9.6
EF coils	Modified steel	30	43.0	315.0	10.5
EF shield	Modified steel	30	43.9	347.0	11.6
	B ₄ C		18.8	47.0	1.6
	TOTAL		62.7	394.0	13.2
Divertor shield	zone 1	1	2.3	14.2	14.2
	zone 2		5	6.7	41.2
TOTAL CLASS-C WASTE			199.0	1363.0	151.0

^(a) Based on operation at 18 MW/m² of neutron wall loading.

ium, need to be controlled in the vanadium alloy below currently expected levels.

Table 7 summarizes the TITAN materials and related quantities for Class-C disposal. The total weight in the FPC of the TITAN-I reactor is about 1,363 tonnes, of which about 73% is from the magnet systems that last the plant lifetime. The reactor torus (first wall, blanket, and the divertor module) is replaced annually and constitutes only 4% of the total weight of the FPC. The balance of the weight is from the shield, which has a five-year lifetime. The average annual-replacement mass of the FPC is about 150 tonnes.

The TITAN-I divertor plates are fabricated with a tungsten armor because of its low sputtering properties. The waste-disposal rating of the divertor plates is estimated to be a factor of 10 higher than for Class-C disposal after one year of operation. The annual disposal mass of this non-Class-C waste is 0.35 tonnes, about 0.23% of the average annual discharge mass.

12. Maintenance

The TITAN reactors are compact, high-power-density designs. The small physical size of these reactors permits each design to be made of only a few pieces, allowing a single-piece maintenance approach [7,8]. All components that must be changed during the sched-

uled maintenance are replaced as a single unit. Furthermore, because of the small physical size and mass of the TITAN-I FPC, the maintenance procedures can be carried out through vertical lifts, allowing a much smaller reactor vault.

Potential advantages of single-piece maintenance procedures are identified:

- (1) Shortest period of downtime resulting from scheduled and unscheduled FPC repairs;
- (2) Improved reliability resulting from integrated FPC pretesting in an on-site, nonnuclear test facility prior to committing the FPC to nuclear service;
- (3) No adverse effects resulting from the interaction of new materials operating in parallel with radiation-exposed materials;
- (4) Ability to modify continually the FPC to benefit from technological developments;
- (5) Recovery from unscheduled events would be more standard and rapid. The entire reactor torus is replaced and the reactor is brought back on line with the repair work being performed afterwards, outside the reactor vault.

The lifetime of the TITAN-I reactor torus (first wall, blanket, and divertor modules) is estimated to be 15 MWy/m², requiring the replacement of the reactor torus on a yearly basis for operation at 18 MW/m² of neutron wall loading at 76% availability. The hot shield, which is estimated to have a lifetime of five years, is made of two pieces with the upper hot shield removed

during the maintenance procedures and reused in the next replacement of the reactor torus.

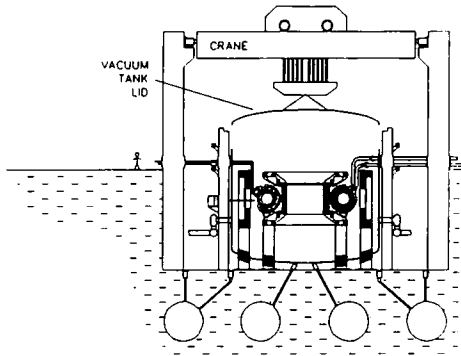
Seventeen principal tasks must be accomplished for the annual, scheduled maintenance of the TITAN-I FPC. These steps are listed in Table 8. Vertical lifts have been chosen for the component movements during maintenance. The most massive components lifted during TITAN-I maintenance are the upper OH-coil set (OH coils 2 through 5) and the upper hot shield.

Each weighs about 150 tonnes, which can be easily managed by conventional cranes. The four major component lifts are illustrated in Fig. 9.

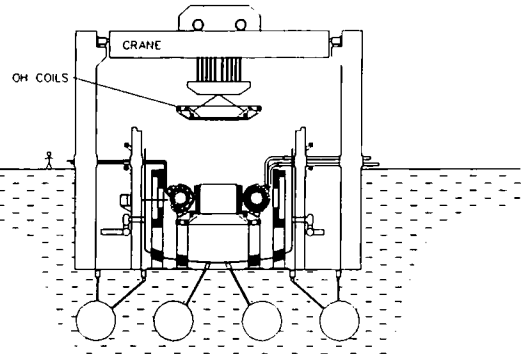
An important feature of the TITAN design is the pretest facility. This facility allows the plant personnel to test fully the new torus assembly in a non-nuclear environment prior to committing it to full-power operation in the reactor vault. Any faults discovered during pretesting can be quickly repaired using inexpensive

TITAN-I MAINTENANCE LIFTS

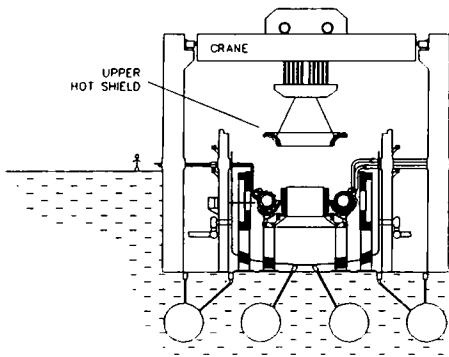
(1) VACUUM TANK LID



(2) UPPER OH COILS



(3) UPPER HOT SHIELD



(4) TORUS ASSEMBLY

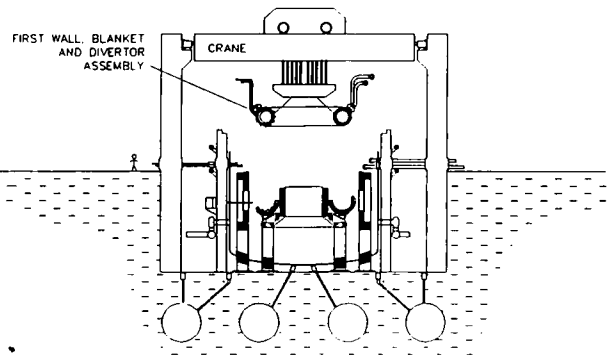


Fig. 9. Four major crane lifts required for the TITAN-I maintenance.

Table 8
Principal tasks during the TITAN-I maintenance procedure

1. Orderly shutdown of the plasma and discharge of the magnets;
2. Continue cooling the FPC at a reduced level until the decay heat is sufficiently low to allow cooling by natural convection in the argon atmosphere;
3. During the cool-down period:
 - a. Continue vacuum pumping until sufficient tritium is removed from the FPC,
 - b. Break vacuum (valve-off vacuum pumps and cut weld at vacuum tank lid),^(a)
 - c. Remove vacuum-tank lid to the lay-down area,
 - d. Disconnect electrical and coolant supplies from the upper OH-coil set;
4. Drain lithium from the FPC;
5. Lift OH-coil set and store in the lay-down area;
6. Disconnect lithium-coolant supplies;^(a)
7. Lift upper shield and store in the lay-down area;
8. Lift the reactor torus and move to the hot cell;^(a)
9. Inspect FPC area;
10. Install the new, pretested torus assembly;^(a)
11. Connect lithium supplies;^(a)
12. Replace upper shield and connect shield-coolant supplies;
13. Replace the upper OH-coil set and connect electrical and coolant supplies;
14. Hot test the FPC;^(b)
15. Replace vacuum-tank lid and seal the vacuum tank;^(a)
16. Pump-down the system;^(c)
17. Initiate plasma operations.

^(a) The time required to complete these tasks is likely to be longer for a modular system than for a single-piece system, assuming similar configuration.

^(b) The new torus assembly is pretested and aligned before commitment to service. Only minimal hot testing would be required.

^(c) The TITAN-I reactor building is filled with argon gas and the replacement torus is also stored in argon atmosphere. Therefore, the pump-down time would be short.

hands-on maintenance. A comprehensive pretest program could greatly increase the reliability of the FPC, hence increasing the plant overall availability.

13. Summary and key technical issues

The TITAN reversed-field-pinch (RFP) fusion-reactor study [1] is a multi-institutional research effort 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, COE), operational

(maintenance and availability), safety, and environmental features of high mass-power-density (MPD) fusion systems.

Two different designs, TITAN-I and TITAN-II, use RFP plasmas operating with essentially the same parameters. Both have a net electric output of about 1000 MWe, are compact, and have a high MPD of about 800 kWe/tonne of FPC. The MPD and the FPC power density of several fusion-reactor designs and a fission pressurized-water reactor (PWR) are shown in Fig. 7 of the Introduction on p. 77 and compared with those of the TITAN reactors. The TITAN study shows that with proper choice of materials and FPC configuration, the attractive safety and environmental features of fusion need not be sacrificed in compact reactors. The TITAN designs would meet the U.S. criteria for the near-surface disposal of radioactive waste (Class-C, 10CFR61) [31] and achieve a high level of passive safety assurance [28,29]. A “single-piece” FPC maintenance procedure, unique to high MPD reactors, has been worked out and appears feasible.

Parametric system studies have been used to find cost-optimized designs. The design window for compact RFP reactors includes machines with neutron wall loadings in the range of 10 to 20 MW/m² with a shallow minimum for COE at about 19 MW/m². Reactors in this “design window” are physically small, and a potential benefit of this “compactness” is improved economics. The TITAN study adopted design points at 18 MW/m² in order to quantify and assess the technical feasibility and physics limits for such high-MPD reactors.

The TITAN-I design is a lithium, self-cooled design with a vanadium-alloy (V-3Ti-1Si) structural material. The magnetic field topology of the RFP is favorable for liquid-metal cooling. The first wall and blanket consist of single-pass, poloidal-flow loops aligned with the dominant poloidal magnetic field. Use of MHD turbulent-flow heat transfer at the first wall is made possible by the low magnetic interaction parameter. The TITAN-I thermal-hydraulic design can accommodate up to 5 MW/m² 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. 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 [13]. The lithium coolant in the blanket circuit flowing in the poloidal direction is also used as the electrical conductor of the toroidal-field and divertor coils. The IBC concept eliminates the need to shield the coils and

allows direct access to the blanket and shield assemblies, thereby easing the maintenance procedure.

The general arrangement of the TITAN-I reactor is illustrated in Fig. 1 of this paper and Figs. 2 and 3 of the Introduction on p. 73. The entire FPC is contained in a vacuum tank. A "single-piece" FPC maintenance procedure is used, in which the first wall and blanket are removed and replaced by vertical lift of the components as a single unit. 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 installation in the reactor vault.

All of the FPC primary-coolant ring headers are located above the torus, which 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. 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-afterheat 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 firstwall LOCA and system LOFA (the most severe accident postulated for TITAN-I) is 990°C. 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.

The results from the TITAN study support the technical feasibility, economic incentive, and operational attractiveness of compact, high-MPD RFP reactors. The road towards compact RFP reactors, however, contains major challenges and uncertainties, and many critical issues remain to be resolved. The TITAN study has identified the key physics and engineering issues that are central to achieving reactors with the features of TITAN-I and TITAN-II.

The experimental and theoretical bases for RFPs have grown rapidly during the last few years [6], but a large degree of extrapolation to TITAN-class reactors is still required. The degree of extrapolation is one to two orders of magnitude in plasma current and temperature and two to three orders of magnitude in energy confinement time. However, the TITAN plasma density, poloidal β , and plasma current density all are close to present-day experimental achievements. The TITAN study has 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 RFP) is extremely important. Second, the physics of toroidal-field divertors in RFPs must be examined, and the impact of the magnetic separatrix on RFP confinement must be studied. High-recycling divertors and the predicted high-density, low-temperature scrape-off layer must be confirmed. Third, current drive by magnetichelicity injection utilizing the natural relaxation process in RFP plasma is predicted to be efficient [9,10] but experiments on oscillating-field current drive (OFCD) are inconclusive. Testing OFCD in higher temperature plasmas must await the next generation of RFP experiments.

The key engineering issues for the TITAN-I FPC have also been defined. Data on the irradiation behavior of V-3Ti-1Si are needed to estimate accurately the lifetime of the TITAN-I first wall. Compatibility of the vanadium-base alloy with lithium coolant and the effects of a bimetallic loop also require more experimental data. Further experimental data on irradiation behavior of ceramic insulators are needed.

The low value of the toroidal field in the RFP allows high coolant velocities, permitting operation in the turbulent-flow regime, with the associated high heat-transfer coefficients. Further experimental data on turbulent-flow heat-transfer capability of liquid metals are crucial to verify the TITAN-I thermal-hydraulic design.

The design of the impurity-control system poses some of the most severe problems of any component. Physics operation of high-recycling toroidal-field divertors in RFPs should be experimentally demonstrated and the impact of OFCD on the divertor performance studied. Cooling of the TITAN-I divertor plate requires experimental data on turbulent-flow heat transfer in liquid-metal systems. Fabrication of the tungsten divertor plate remains to be demonstrated, and the degree of precision needed for target shaping and for control of the position of the plasma separatrix are particularly difficult tasks.

The TITAN-I molten-salt tritium-recovery process needs large-scale demonstration. Any fusion reactor

with vanadium first walls may encounter the problem of plasma-driven permeation (PDP) of tritium. The extent of PDP should be experimentally investigated.

The TITAN-I design uses many safety-design features to achieve a high level of safety assurance. Further detailed analyses of the response of the TITAN-I FPC to accidents, including lithium fires, are needed to confirm the findings. Data are needed at elevated temperatures on vanadium alloys, such as the volatilization of radioactive products. To qualify for Class-C waste disposal, some impurity elements need to be controlled in the vanadium alloy to below ppm levels.

In summary, the results from the TITAN study support the technical feasibility, economic incentive, and operational attractiveness of compact, high-MPD RFP reactors. It must be emphasized, nevertheless, that their design remains a most difficult engineering challenge. Also, the RFP plasma itself must operate in the manner outlined (i.e., with toroidal-field divertors, with a highly radiative core plasma, and at steady state). Future research will be required to meet the physics and technology requirements of TITAN-like RFP reactors.

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