Fusion Engineering and Design 9 (1989) 367–373
North-Holland, Amsterdam

OVERVIEW OF THE TITAN-I FUSION-POWER CORE

S.P. GROTZ [1], N.M. GHONIEM [1], and The TITAN Research Group
J.R. BARTLIT [3,*], C.G. BATHKE [3], J.P. BLANCHARD [1], E.T. CHENG [2], Y. CHU [1],
R.W. CONN [1], P.I.H. COOKE [1,†], R.L. CREEDON [2], E. DABIRI [6], W.P. DUGGAN [4],
O. FISCHER [2,**], P.J. GIERSZEWSKI [7], G.E. GORKER [6], M.Z. HASAN [1], C.G. HOOT [2],
D.C. KEETON [6], W.P. KELLEHER [4], C.E. KESSEL [1], R.A. KRAKOWSKI [3], O. KVETON [7],
D.C. LOUSTEAU [6], R.C. MARTIN [1], R.L. MILLER [3], F. NAJMABADI [1], R.A. NEBEL [3],
G.E. ORIENT [1], A.K. PRINJA [1,††], K.R. SCHULTZ [2], S. SHARAFAT [1], D. STEINER [4],
D.K. SZE [5], S.L. THOMSON [6], S.G. VISSER [2], E.L. VOLD [1], K.A. WERLEY [3], C.P.C. WONG [2]

[1] *Department of Mechanical, Aerospace and Nuclear Engineering and Institute for Plasma and Fusion Research, University of California, Los Angeles, Los Angeles, CA 90024-1597, USA*
[2] *General Atomics.*
[3] *Los Alamos National Laboratory.*
[4] *Rensselaer Polytechnic Institute.*
[5] *Argonne National Laboratory.*
[6] *Fusion Engineering Design Center.*
[7] *Canadian Fusion Fuels Technology Project.*

The TITAN reactor is a compact (major radius of 3.9 m and plasma minor radius of 0.6 m), high neutron wall loading (~18 MW/m^2) fusion energy system based on the reversed-field pinch (RFP) confinement concept. The reactor thermal power is 2918 MWt resulting in net electric output of 960 MWe and a mass power density of 700 kWe/tonne. The TITAN-I fusion power core (FPC) is a lithium, self-cooled design with vanadium alloy (V–3Ti–1Si) structural material. The surface heat flux incident on the first wall is ~ 4.5 MW/m^2. 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. A unique feature of the TITAN-I design is the use of the integrated-blanket-coil (IBC) concept. With the IBC concept the poloidal flow lithium circuit is also the electrical conductor of the toroidal-field and divertor coils. Three dimensional neutronics analysis yields a tritium breeding ratio of 1.18 and a molten salt extraction technique is employed for the tritium extraction system. Almost every FPC component would qualify for Class C waste disposal. The compactness of the design allows the use of single-piece maintenance of the FPC. This maintenance procedure is expected to increase the plant availability. The entire FPC operates inside a vacuum tank, which is surrounded by an atmosphere of inert argon gas to impede the flow of air in the system in case of an accident. The top-side coolant supply and return virtually eliminate the possibility of a complete LOCA occurring in the FPC. The peak temperature during a LOFA is 991°C.

1. Introduction and background

The TITAN Reversed-Field Pinch (RFP) fusion reactor research effort [1,2] has been undertaken to determine the technical feasibility and key development issues of an RFP fusion reactor, especially at high power density, and to determine the potential economics (cost of electricity), operations, safety, and environmental features of high-mass-power-density fusion systems. Two different detailed designs, TITAN-I and TITAN-II, have emerged and parametric systems studies have been utilized both to optimize the point designs and to determine the parametric design window associated with each approach. This combination of parametric and point design work is referred to as a 'parapoint' study. This paper summarizes the engineering efforts of

---

[*] TSTA program.
[†] Permanent address: UKAEA Culham Lab., Abingdon, Oxon OX14 3DB, UK.
[**] Permanent address: Swiss Federal Inst. for Reactor Research (EIR), Würenlingen, Switzerland.
[††] Present address: University of New Mexico, Albuquerque, NM 87107, USA.

the TITAN research team on TITAN-I, a self-cooled lithium design with vanadium structure. TITAN-II is an aqueous breeder loop-in-pool design which is summarized in [3]. Complete details of the TITAN-I and TITAN-II fusion power core designs can be found in the TITAN Final Report [1]. Summaries of the TITAN systems studies, magnetics and so on can be found in the same proceedings as [2].

The TITAN conceptual designs are DT burning, approximately 1000 MWe power reactors based on the RFP confinement concept. The designs are compact, have a high neutron wall loading of 18 MW/m^2 and a mass power density of 700 kWe/tonne. The inherent characteristics of the RFP confinement concept make fusion reactors with such a high mass power density possible.

The reversed-field pinch [4], like the tokamak, belongs to a class of axisymmetric, toroidal confinement systems that utilitze both toroidal (B_ϕ) and poloidal (B_θ) magnetic fields to confine the plasma. The fundamental property of the RFP is that the field configuration and toroidal field reversal are the result of the relaxation of the plasma to a near-minimum-energy state, as proposed by Taylor [5,6]; the generation of the reversed toroidal field is the natural consequence of this relaxation process. In the tokamak, stability is provided by a strong toroidal field $B_\phi \gg B_\theta$ such that the safety factor exceeds unity, that is, $q > 1$. In the RFP, on the other hand, strong magnetic shear produced by the radially varying (and decreasing) toroidal field stabilizes the plasma with $q < 1$ and relatively modest B_ϕ. RFPs, therefore, can operate with a large ratio of plasma current to toroidal field and stability constraints on the aspect ratio are removed. High-current-density operation and ohmic heating to ignition are possible, and the choice of the aspect ratio can be made solely on the basis of engineering considerations. Also, the RFP can operate at a high total beta, thereby allowing operation at high power density. The experimentally measured poloidal beta values are in the range 10–20%. Furthermore, the low magnetic field strength on the external conductors results in a high engineering beta defined as the ratio of the plasma pressure to the magnetic field pressure at the magnets. Low current-density and less massive resistive coils are therefore possible. The TITAN plasma is ohmically heated to ignition using resistive copper ohmic heating (OH) coils. The toroidal-field and divertor coils are also normal-conducting, Integrated-Blanket-Coil (IBC) for TITAN-I and copper coils for TITAN-II. The equilibrium field is produced by a pair of superconducting coils to reduce the required recirculating power.

Extensive parametric system studies have been performed to select and optimize the design point and then to determine the associated design window for an attractive RFP reactor. These design points were then subjected to detailed engineering analysis and subsystem design. These trade studies pointed to an attractive RFP reactor regime of operation with neutron wall loadings in the range of 10–20 MW/m^2 and mass power densities in the range of 500–700 kWe/tonne in which COE is an insensitive function of the neutron wall loading. Reference design point, corresponding to 18 MW/m^2 of neutron wall loading were chosen for TITAN designs in order to determine the technical feasibility and key developmental issues for the entire design window.

Another feature of these TITAN-class reactors is that the cost of the FPC is a small fraction of the overall plant cost (< 10%). This makes the economics of the reactor less sensitive to changes in the plasma performance or in the unit cost of FPC components. Moreover, since the FPC is smaller and cheaper, a rapid development program at lower cost is possible, changes in the FPC design would not introduce large cost penalties, and the economics of learning-curves can be exploited.

2. Configuration

The general arrangement of the TITAN-I FPC is illustrated in fig. 1. The entire FPC is contained in a vacuum tank to ease the remote making and breaking of vacuum welds during scheduled and unscheduled maintenance. All of the primary coolant ring-headers are above the torus so that in the event of a break in the primary piping, coolant will remain in the torus and the most severe consequence will be that of a LOFA. The flow paths are aligned with the dominant, poloidal field so that MHD consequences are reduced. The coolant flow paths are illustrated in fig. 2. The first wall and blanket are made of extruded vanadium alloy tubing and are single-pass, poloidal flow. The shield assembly has two zones, a 30 cm, 30% structure zone immediately behind the blanket and a 15 cm, 90% structure zone at the back to reduce the neutron flux to the OH coils. All of the structural material in the FPC is vanadium alloy. Exclusion of other, high-activation alloys (e.g., HT-9) reduces peak temperature during LOFAs and allows for Class-C waste disposal. Operating characteristics of the FPC are listed in table 1.

The integrated-blanket-coil (IBC) concept [7] is used in TITAN-I. An electric current passed through the

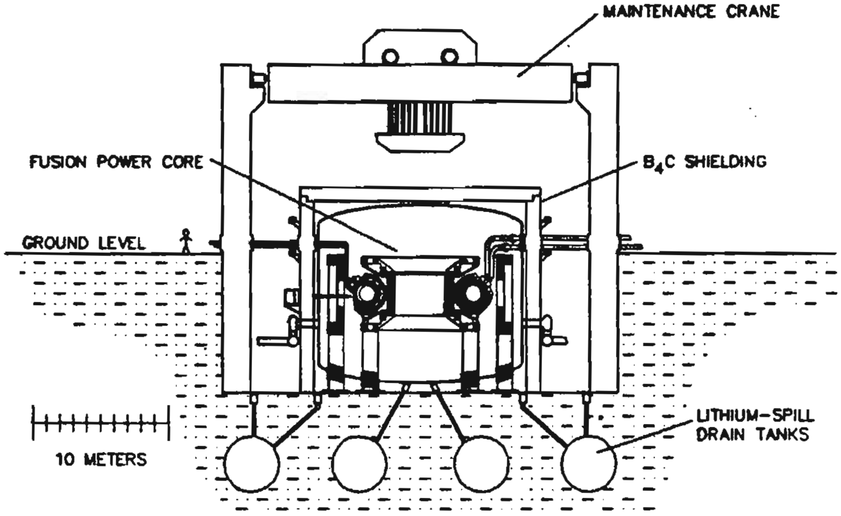

Fig. 1. General arrangement of the TITAN-I fusion power core.

poloidal-flow lithium circuit provides the toroidal field required for the TF and divertor coils. The IBC concept eliminates the need for shielding the two coils and reduces the number of components needing access during maintenance. All of the magnets are normal conducting with the exception of the two superconduct-

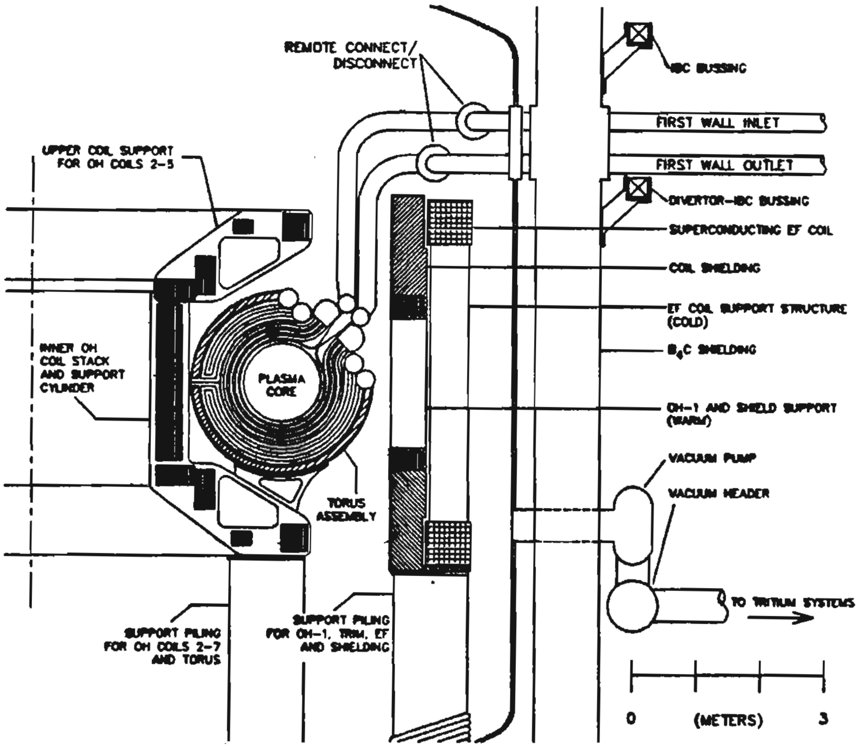

Fig. 2. Poloidal cross section of the TITAN-I fusion power core.

Table 1
Major operating parameters of TITAN-I

Dimensions	
Major plasma radius	3.9 m
Minor plasma radius	0.6 m
First wall minor radius	0.66 m
First wall surface area	160 m^2
Thickness of first wall, blanket and shield	0.77 m
First wall pipes diameter	10.5 mm
IBC pipes diameter	52.5 mm
Plasma	
Neutron wall loading	18 MW/m^2
Plasma density	9.45×10^{20} m^{-3}
Poloidal beta	0.22
Poloidal field at first wall	5.44 T
Toroidal field at first wall	0.36 T
Power	
Fusion power	2288 MW
Total thermal power	2918 MW
Gross electric power	1284 MW
Net electric power	998 MW
Mass power density	700 kW_e/tonne
Blanket energy multiplication	1.2
Thermal cycle efficiency	
Cycle 1	0.37
Cycle 2	0.465
Average	0.44
Net plant efficiency	0.34
Surface heating, peak	
First wall	4.5 MW/m^2
Divertor	7.5 MW/m^2
Volumetric heating, peak	95 MW/m^3
Hydraulic	
Li Coolant inlet temperature	320 °C
Li Coolant outlet temperature	
First wall and divertor	440 °C
IBC and hot-shield	700 °C
Li Coolant pressure, inlet	
Divertor	12.0 MPa
First wall	10.0 MPa
IBC and hod shield	2.9 MPa

ing equilibrium field coils located at the outboard edge of the fusion power core.

TITAN uses three toroidal-field divertors for impurity control. The coils used in the divertors are IBC-type coils similar to those in the blanket. The neutralizer plate is a lithium cooled structure with vanadium-alloy coolant tubes and a tungsten-rhenium surface. The peak heat flux on the divertor plate is 7.5 MW/m^2.

3. Materials

In high power density, compact fusion reactors such as TITAN, the harsh neutron environment limits the choice of structural, shield and insulator materials. Several loading conditions are addressed such as thermal, chemical, radiation, mechanical and electromagnetic. In particular the response of plasma facing materials to radiation, thermal and pressure stresses, and their compatibility with the coolant are of primary concern. Because of the retention of mechanical strength at high temperatures and good thermal properties, vanadium-base alloys are promising materials for structural components. Relative to austenitic and ferritic steels, the vanadium alloys have much better corrosion resistance. Three alloys, V-15Cr-5Ti, VANSTAR and V-3Ti-1Si have been studied. Irradiation, creep and coolant compatibility issues have been investigated and led to the choice of the V-3Ti-1Si alloy as the primary structural material for the TITAN-I design.

4. Neutronics

Tritium breeding, waste disposal, nuclear heating (both during operation and after shutdown), annual replacement mass of vanadium alloy and protection of all magnets in the fusion power core among the list of important isues taken into account in the neutronics design optimization. An important finding is that some nuclear performance characteristics such as decay heat, waste disposal rating, and atomic displacement in structural alloys are dramatically improved if the lithium coolant is enriched with ^{6}Li. Therefore, the ^{6}Li enrichment in lithium is chosen to be 30% in the reference design.

The first wall and IBC components have a lifetime of one full power year. The hot shield is replaced every five full power years assuming the maximum atomic displacement in the vanadium alloy structure to be 200 dpa. The ohmic heating coils are expected to last for the entire 30 full power years plant lifetime. The limiting factor is radiation damage to the spinel electrical insulator in the magnets, estimated in terms of neutron fluence to be about 2×10^{23} n/cm^2 ($E_n > 0.1$ MeV). The global tritium breeding ratio is 1.18 from a three-dimensional calculation, including the effect of the divertors, while the one-dimensional full coverage calculation gives 1.33. The blanket energy multiplication factor is 1.2.

5. Thermal hydraulics

The major features of the thermal-hydraulic design for the TITAN high wall loading reactor are: (1) alignment of the coolant channels along the dominant poloidal magnetic field, (2) separation of the first wall and blanket coolant circuits thus allowing lower coolant exit temperature for the first wall, and (3) use of MHD turbulent flow heat transfer at the high heat flux first wall, made possible by the low magnetic interaction parameter. A thermal-hydraulic design has emerged that can handle up to 5 MW/m^2 of heat flux on the first wall. The coolant velocity in the first wall tubes is about 20 m/s and in the blanket it is about 0.5 m/s. Material erosion due to high velocity lithium flow in the first wall tubes is estimated to negligible. The total pressure drop in the first wall tubes is about 10 MPa and the resulting primary stress is 4 to 7 times smaller than the allowable stress (e.g. ~ 80 MPa at 650 °C). A two-stage coolant pump, about 5 MPa per stage, is used for the first wall while a single-stage pump is used for the blanket where the pressure drop is about 2 MPa. The total pumping power requirement for coolant circulation is about 3.6% of the net electric output.

The high velocity required to cool the first wall limits the coolant temperature rise to 100 °C (the outlet temperature is 400 °C). Two power-cycle options are considered. One, mix the first wall coolant with the hotter blanket coolant (blanket outlet temperature is 700 °C) and two, have two steam-turbine power cycles which are optimized for the temperature conditions of the first wall and blanket, respectively. The gross thermal efficiency of the latter option is 44% and has been chosen for TITAN-I.

6. Tritium systems

The maximum off-site tritium release is designed to be 10 Ci/d. The tritium flux on the first wall is estimated at $1.5 \times 10^{17}\ cm^{-2}\ s^{-1}$, and 95% of the tritons have energies below 5 eV. With vanadium susceptible to plasma-driven permeation (PDP) and the triton energies very low, superpermeation of the low-energy tritons may result (reduced tritium re-emission and increased permeation into the coolant). The DIFFUSE [8] code gives a minimum of 110 g/d PDP which can be much larger if superpermeation occurs. Extraction of tritium from Li is based on the molten salt technique, adequate for extracting 420 g/d of bred tritium plus PDP at a cost of $5 to $15 million. A tritium concentration of one wppm in Li at equilibrium gives approximately 200 g soluble tritium inventory in the primary coolant loop. A Li secondar loop has an inventory of about 300 g of tritium; use of sodium in the loop would yield about one gram of inventory and cold-trapping is not required. The divertor tritium inventory and coolant permeation are insignificant despite the large fluxes because of the resistance of the tungsten divertor plate to tritium permeation.

The room air detritiation systems can clean up a 5 kg spill of tritium in three days at a capital cost of $5 million. Plasma exhaust gas processing will be based on palladium diffusers. DIFFUSE gives a tritium inventory in the FPC structure between 3 and 7 g and release into the vacuum tank which surrounds the FPC of approximately 6 g/d.

7. Safety

During the study, different fusion power core designs were considered that can have the potential of operating at high neutron wall loading of 18–20 MW/m^2. Safety features have been incorporated into the design from the beginning, with the purpose of designing with passive safety, simplicity, high availability, and low cost.

The key safety feature of the TITAN-I lithium/vanadium fusion power core design is the complete enclosure of the lithium primary loop system is an inert gas-filled confinement building. The blanket containers, vacuum vessel, and confinement building form three barriers to prevent air influx, lithium fires and protect the public from radioactive materials. All piping connections are located at the top of the torus to prevent the complete loss of first wall/blanket coolant during an accident. A blanket tube failure at the low-point of the blanket would lead to a LOCA-situation in the failed pipe only. Since the common connection for all of the blanket pipes is at the top of the torus, the undamaged pipes will retain their lithium inventory. Lithium drain tanks are provided for both the reactor vault and the vacuum tank to reduce passivel the vulnerable blanket lithim inventory. A totally passive system that could drain all the lithium inventory into a fire-safe mode within approximately 30 s is possible. Two-dimensional thermal analyses of the loss of coolant and loss of flow accidents (LOCA and LOFA) in the first wall and blanket regions have been performed. Different design features are selected to prevent LOCAs and to minimize the LOFA peak temperature of the first wall during accidents in order to minimize the potential release of radioactivity. To evaluate this design further, lithium fire accident scenarios are studied by using the LITFIRE [9] code developed by MIT and site boundary dose calculations were performed to understand the potential release of radioactivity under major accident and routine release conditions.

The maximum temperature during a first wall LOCA and system LOFA (the most severe accident postulated for TITAN-I) is 991° C. Thermal creep-rupture analysis of the vanadium structure indicates that failure will not occur during the temperature excursion period of the accident, about 5 to 6 days. The maximum temperature during a lithium-fire is 747° C in the combustion zone. The results from these accident evaluations indicate that the lithium self-cooled design can potentially be passively safe, without reliance on active safety systems.

8. Maintenance

The compact design of the TITAN-I fusion power core reduces the system to a few small and relatively low mass components, making toroidal segmentation of the FPC unnecessary. A single-piece maintenance procedure in which the replaceable first wall and blanket is removed as a single unit is, therefore, possible. The potential advantages of single-piece maintenance procedures are: (1) shortest period of down time resulting from scheduled and unscheduled FPC repairs, (2) improved reliability resulting from integrated FPC pretesting in an on-site, non-nuclear test facility where coolant leaks, coil alignment, thermal expansion effects, etc., would be corrected prior to committing to nuclear service using rapid, and inexpensive, hands-on repair procedures, (3) no adverse effects resulting from the interaction of new materials operating in parallel to radiation damaged materials, and (4) ability to continually modify the FPC design as may be indicated by reactor performance and technological developments.

The TITAN FPC design provides for top access to the reactor with vertical lifts used to remove the components. The number of remote handling procedures is few and the movements are uncomplicated. A high degree of automation is assumed, particularly with the use of powered components throughout the hydraulic and electrical circuits. Extensive use of this type of automation should reduce the required maintenance time to a period that is comparable to that of the balance-of-plant scheduled maintenance (~ 30 d), thereby enabling both tasks to be done in parallel. The annual torus replacement requires that the reusable ohmic-heating coil set and reflector/shield assembly be removed and temporarily stored in a hot cell. The used first wall and blanket assembly is drained and disconnected from the coolant supply system. For safety reasons, the blanket pipes are at the lowest point in the primary circuit. Draining these pipes requires the use of small drain-tubes permanently installed in each blanket pipe. After the majority of the primary loop is gravity-drained, the remaining lithium is pumped out of the blanket through the drain-tubes. After draining, the used torus is then lifted to a processing room where it is cooled and prepared for Class-C waste burial. The new, pre-tested first wall and blanket assembly is then lowered into position and the removal procedure is reversed to complete the replacement process.

9. Summary

The TITAN-I reactor is a compact, high neutron wall loading (~ 18 MW/m^2) fusion energy system based on the reversed-field pinch (RFP) confinement concept. The reactor thermal power is 2918 MW resulting in net electric output of 960 MW and a mass power density of 700 kWe/tonne. The fusion power core is a lithium, self-cooled design with vanadium alloy (V–3Ti–1Si) structural material. The TITAN design utilizes the soft beta limit feature of RFPs and operates with a highly radiative plasma in order to limit the heat flux on the divertor plates to acceptable levels. The surface heat flux incident on the first wall is, therefore, ~ 4.5 MW/m^2. MHD effects had precluded the use of liquid metal coolants for high heat flux components in previous designs, 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. The thermal-hydraulic analysis shows a reasonable MHD pressure drop (~ 12 MPa in the first wall circuit and ~ 3 MPa in the blanket) and a modest pumping power requirement (~ 45 MWe) with a thermal power cycle efficiency of ~ 44%.

A unique feature of the TITAN-I design is the use of the integrated-blanket-coil (IBC) concept. With the IBC concept the poloidal flow lithium circuit is also the electrical conductor of the toroidal-field and divertor coils. Use of the IBC concept eliminates the need for TF-coil shielding and simplies the maintenance procedure. Three dimensional neutronics analysis yields a tritium breeding ratio of 1.18. A molten salt extraction technique is employed for the tritium extraction system. The high neutron wall loading of the TITAN reactor results in a one year lifetime for the first wall and blanket. The shield, however, will be replaced every five years. Almost every FPC component would qualify for Class-C waste disposal.

The compactness of the design allows the use of single-piece maintenance of the FPC. The use of single-piece maintenance procedures is expected to provide the shortest period of downtime resulting from scheduled and unscheduled FPC repairs. Reduced downtime is achieved because the replacement FPC is fully pre-tested in an on-site, non-nuclear test facility. This maintenance procedure is expected to increase the plant availability. The general arrangement of the fusion power core provides for vertical lifts to remove the core components during maintenance.

The entire FPC operates inside a vacuum tank, which is surrounded by an atmosphere of inert argon gas to impede the flow of air in the system in case of an accident. The top-side coolant supply and return virtually eliminate the possibility of a complete LOCA occurring in the FPC. The peak temperature during a LOFA is 991° C.

Acknowledgement

Work supported in part by the United States Department of Energy under Contract No. DE-FG03-86ER52126.

References

[1] F. Najmabadi, R.W. Conn, N.M. Ghoniem, S.P. Grotz, J. Blanchard et al., The TITAN reversed-field pinch fusion reactor study; the final report, UCLA-PPG-1200, Joint Report of University of California – Los Angeles, GA Technologies, Inc., Los Alamos National Laboratory, and Rensselaer Polytechnic Institute, March 1988. Also see F. Najmabadi, N. M. Ghoniem, R.W. Conn et al., The TITAN reversed-field pinch fusion reactor study; scoping phase report, UCLA-PPG-1100 (January 1987).

[2] R.W. Conn, F. Najmabadi and the TITAN Research Group, The TITAN reversed-field pinch fusion reactor study, Proc. IEEE 12th Symp. on Fusion Engineering, Monterey, California (October 1987).

[3] C.P.C. Wong, R.L. Creedon, S.P. Grotz, E.T. Cheng, S. Sharafat et al., The TITAN-II reversed-field pinch reference aqueous blanket design, in Proc. Int. Symp. on Fusion Nuclear Technology, Tokyo (Japan April 10–19, 1988).

[4] H.A. Bodin, R.A. Krakowski and O. Ortolani, The reversed-field pinch: from experiment to reactor, Fusion Technol. 10 (1986) 307.

[5] J.B. Taylor, Relaxation of toroidal plasma and generation of reversed magnetic fields, Phys. Rev. Lett. 33 (1974) 1139–1141.

[6] J.B. Taylor, Relaxation of toroidal discharges, Proc. 3rd Topical Conf. on Pusled High-Beta Plasmas, Abingdon, September 1975 (Pergamon Press, London, 1976) p. 59.

[7] D. Steiner, R.C. Block and B.K. Malaviya, The intergrated blanket-coil concept applied to the poloidal field and blanket systems of a tokamak reactor, Fusion Technol. 7 (1985) 66.

[8] M.I. Baskes, DIFFUSE 83, Sandia National Laboratory, SAND-83-8231 (1983).

[9] E. Yachimiak, V. Gilberti and M.S. Tillack, LITFIRE User's Guide, MIT report, PFC/RR-83-11 (June, 1983).