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Tokamak Fusion Neutron Source Requirements for Nuclear Applications

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Abstract The potential near-term role for fusion in closing the nuclear fuel cycle was examined in a series of design studies for sub-critical fast transmutation reactors driven by tokamak fusion neutron sources.

1. Introduction

For many years there has been a substantial international R&D activity devoted to closing the nuclear fuel cycle. During the 1990s this activity emphasized the technical evaluation of transmutation reactors that would fission the transuranic (TRU) content of the accumulating spent nuclear fuel (SNF) discharged from conventional nuclear power reactors[1-4]**,** in order to reduce the requirements for long-term geological high-level waste repositories (HLWRs) for the storage of SNF. With the recently increasing recognition that nuclear power is the only environmentally sustainable way to meet the world's expanding energy requirements in the near-term, the emphasis in the new century has broadened to also include extracting more of the potential energy content in uranium by first transmuting the "fertile" ^{238}U into fissionable ^{239}Pu. This growing realization of the necessity of an expanded global role for nuclear power has led to a number of U. S. government policy initiatives aimed at closing the nuclear fuel cycle—the Advanced Fuel Cycle Initiative (AFCI), the Generation-IV Initiative (GEN-IV) and most recently the Global Nuclear Energy Partnership (GNEP).

There would be advantages in being able to operate the transmutation reactors sub-critical, with a neutron source to provide the neutrons needed to maintain the fission chain reaction at full power, e.g. the achievement of higher levels of burnup of a given batch of TRU fuel, higher fractions of TRU fuel in the reactor. Almost all of the studies[1-4] of sub-critical transmutation reactors in the 1990s were based on use of a D+ accelerator with a spallation target as a neutron source, although there were a few studies of the use of D-T fusion neutron sources.

The concept of using a D-T tokamak fusion neutron source based on ITER physics and technology to drive a sub-critical fast transmutation reactor based on nuclear and separations technologies being evaluated in the GNEP initiative has been developed in a series of studies[5-16] at Georgia Tech over the past several years. The general design objective was a 3000 MWth, passively safe, sub-critical fast reactor driven by a fusion neutron source that could fission the TRU in the SNF discharged annually by three 1000 MWe LWRs. The general fuel cycle objective was > 90% burnup of this TRU (in order to reduce the HLWR requirements by an order of magnitude relative to the present once-through LWR fuel cycle) while minimizing the nuclear fuel reprocessing steps. The designs were constrained to use ITER physics and technology for the fusion neutron source, to use nuclear and reprocessing technology being evaluated in the GNEP studies, to use extensions of existing nuclear fuel technology but with TRU, and to achieve tritium self-sufficiency for the fusion neutron source.

2. FTWR and GCFTR Studies

Sub-critical transmutation reactors based on two of the nuclear technologies being developed in the GEN-IV studies were examined. The Fusion Transmutation of Waste Reactor (FTWR) series of studies was based on a variant of the GEN-IV Sodium or Lead Cooled Fast Reactors-- fast-spectrum reactors using a metal fuel consisting of TRU alloyed with zirconium in a zirconium matrix and cooled by a liquid metal (Li17Pb83 eutectic), which also served as the tritium breeder. The Gas Cooled Fast Transmutation Reactor (GCFTR) series of studies was based on a variant of the GEN-IV Gas Cooled Fast Reactor--a fast-spectrum reactor using TRU-oxide fuel in coated TRISO particle formed in a SiC matrix cooled by He, with solid Li_2O for tritium breeding. Both the FTWR and GCFTR cores were annular and located outboard of the toroidal plasma chamber, as indicated in Fig. 1 for the GCFTR design. The core plus plasma chamber were surrounded first by a reflector (tritium breeding blanket for GCFTR) and then by a shield to protect the magnets from radiation damage and heating,

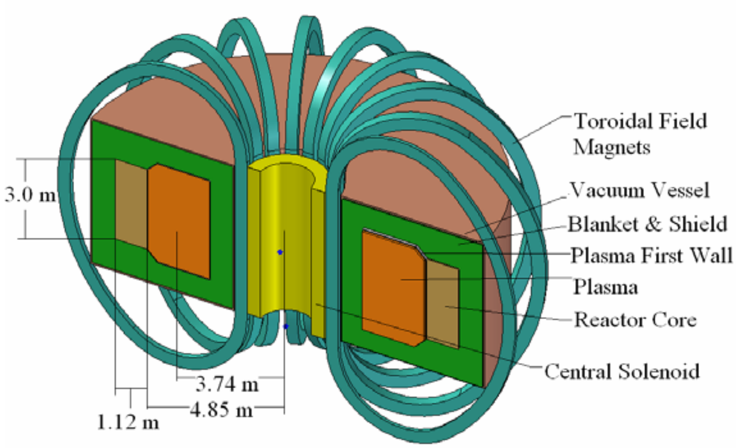

Fig. 1 Gas Cooled Fast Transmutation Reactor

The ANL metal fuel, liquid metal cooled reactor design[17] was adapted to accommodate a different coolant and TRU-Zr fuel for the FTWR designs. The fast, gas-cooled reactor designs being developed in the GEN-IV studies guided the choice of the GCFTR core design, and the coated fuel particle technology being developed in the Next Generation Nuclear Plant (NGNP) program was adapted for the TRU-oxide fuel for the GCFTR. The fusion technology was based on the ITER design. Ferritic or ODS steel was used as the structural material. The superconducting magnet design was based directly on the ITER superconducting magnet system. The first-wall and divertor designs were based on adaptations of the ITER designs to accommodate different coolants. The ITER heating and current drive system was adapted. The reference materials compositions chosen for the FTWR and GCFTR designs are given in Table I.

A series of design studies[6-8,12, 13] was performed for the FTWR. An additional objective of the original FTWR study[6] was to achieve minimum size by using liquid nitrogen cooled Cu magnets. The second FTWR-SC study[7] was a modification of the FTWR design to replace the Cu magnets with superconducting magnets. The third FTWR-AT study[8]

TABLE I REFERENCE MATERIALS COMPOSITION OF FTWR AND GCFTR

Component	**FTWR**	**GCFTR**
Reactor		
Fuel	TRU-Zr metal in Zr matrix	TRU-oxide TRISO,SiC matrix
Clad/structure	FeS/FeS	ODS/ODS
Coolant	LiPb	He
Trit. Breeder	LiPb	Li_2O
Reflector	FeS, LiPb	ODS, He, Li_2O
Shield	FeS, LiPb, B_4C, ZrD_2, W	ODS, HfC, Ir, Cd, WC, B_4C, He
Magnets	NbSn,NbTi/He ($OFHC/LN_2$)	NbSn/He
First-Wall	Be-coated FeS, LiPb	Be-coated ODS, He
Divertor	W-tiles on Cu-CuCrZr, LiPb	W-tiles on Cu – CuCrZr, He

investigated the reduction in size that could be achieved in a superconducting design by using advanced tokamak physics. By repeated recycling of the fuel, with reprocessing, > 90% TRU burnup could be achieved in a fuel cycle that required only (P_{fus} < ≈200 MW)[11].

An additional objective of the GCFTR studies was to achieve > 90% burnup of transuranics in the coated fuel particles with minimal or no reprocessing of the coated TRU particles. During the later stages of the GCFTR-1 study[9] it became apparent that simply using the ITER superconducting magnet thicknesses was too conservative, and the GCFTR-2 study[10] was performed to take this reduced magnet thickness into account. A fuel cycle study[14] indicated that, like the FTWR, the GCFTR could achieve > 90% TRU burnup by repeated recycling with reprocessing, with the same modest fusion neutron source (P_{fus} < ≈200 MW), but that higher fusion powers would be required to achieve this level of burnup without reprocessing.

The GCFTR-3 study[15] demonstrated 1) that the fusion neutron source strength could be extended (to P_{fus} ≈ 400-500 MW) without increasing the size or significantly exceeding the present ITER physics database or magnet systems structural limits, by increasing the current to 10 MA, and 2) that such a neutron source was sufficient to achieve > 90% TRU burnup without reprocessing.

The radial build dimensions of the FTWR and GCFTR concepts are given in Table II.

TABLE II RADIAL BUILD (m) OF FTWR AND GCFTR DESIGNS

Parameter	FTWR	FTWR-SC	FTWR-A	GCFTR	GCFTR-2	GCFTR-3
Major Radius[e], R_0	3.10	4.50	3.86	4.15	3.74	3.76
Fluxcore, R_{fc}	1.24	1.10	0.65	0.66	0.66	0.88
CS+TF, Δ_{mag}	0.57	1.68	1.20	1.50	1.13	0.91
Refl+Shld, Δ_{rs}	0.40	0.65	0.90	0.86	0.87	0.89
Plasma, a_{plasma}	0.89	0.90	1.10	1.04	1.08	1.08
Core						
Inner Radius, R_{in}	4.00	5.40	5.00	5.25	4.84	4.85
Radial Width, W	0.40	0.40	0.40	1.12	1.12	1.12
Height, H	2.28	2.28	2.28	3.00	3.00	3.00

3. Fuel Cycle Analysis

The TRU fuel would be fissioned in "batches", each of which would be irradiated for a "burn cycle" then moved to a new location in the reactor and irradiated for another burn cycle, etc., until it was burned for 5 burn cycles. Once equilibrium is reached, the core loading at the beginning of a burn cycle would have 1 batch of fresh fuel and 1 batch each of once, twice, thrice and four-times burned fuel. If the TRU burnup after the fifth burn cycle was > 90%, the batch of depleted fuel would be deposited in a high-level-waste (HLW) repository; on the other hand, if the TRU burnup was significantly less than 90% the fuel would be reprocessed to remove fission products and recover the TRU to be refabricated and recycled through another 5-batch fuel cycle in the reactor.

The multiplication constant (k_{eff}) of the core decreases with TRU burnup, but the fusion neutron source level (fusion power) can be increased with TRU burnup to compensate the decrease in k_{eff} and maintain the TRU burnup rate (fission power level) constant. The maximum TRU burnup achievable depends on the minimum k_{eff} that can be compensated, hence on the maximum fusion power available. Table III summarizes three different fuel cycles that were examined for GCFTR-3. It is clear that rather modest fusion powers (< 200 MW) would suffice in fuel cycles with reprocessing, but that fusion power ≥ 400 MW is needed to achieve > 90% TRU burnup without reprocessing.

Table III: EQUILIBRIUM 5-BATCH FUEL CYCLES FOR 3000 MWt GCFTR[15]

Parameter			
Burn cycle length, d	600	1200	2400
5-batch residence, y	8.2	16.4	32.9
TRU burn/residence, %	24.9	49.7	93.7
SNF disposed, MT/yr	101	101	95
Fast fluence/residence, 10^{23} n/cm^2	0.7	1.3	4.3
Begin burn cycle k_{eff}	0.987	0.917	0.671
End burn cycle k_{eff}	0.927	0.815	0.611
Begin burn cycle P_{fus}, MW	13	83	329
End burn cycle P_{fus}, MW	73	185	389

4. Tokamak Neutron Source Plasma Physics

Conservative ITER-like physics has been adopted for the design of the FTWR and GCFTR tokamak neutron sources. A reference normalized beta β_N = 2.0% was chosen, although operation at β_N values up to 2.5% could be justified on the basis of present experience. A confinement multiplier H = 1.0 relative to the IPB98(y,2) energy confinement scaling was adopted. The line average electron density was fixed at 75% of the Greenwald density limit to avoid confinement degradation at higher densities. An edge safety factor q_{95} = 3 was specified to avoid MHD instabilities.

Standard aspect ratio – current (I_p-A) analysis[18] was employed to determine the major design parameters of the neutron source. In this approach, the major geometric and operational parameters are expressed in terms of the aspect ratio A and plasma current I_p, taking into account the various physics and engineering constraints[19] as well as the radial build constraint. Based on such analyses, an aspect ratio and a corresponding plasma current were selected for the various FTWR and GCFTR designs. The resulting major design parameters of the tokamak neutron source are listed in Table IV. Two of the FTWR and two of the GCFTR designs were based on P_{fusion}< 200 MW, but the GCTFR-3 design used a higher plasma current of 10 MA to achieve P_{fusion} = 400-500 MW and use of AT parameters led to $P_{fus} \geq$ 500 MW in FTWR-AT.

TABLE IV TOKAMAK NEUTRON SOURCE PARAMETERS FOR FTWR AND GCFTR

Parameter	FTWR [6]	FTWR -SC[7]	FTWR -AT[8]	GCFTR [9]	GCFTR -2[10]	GCFTR -3[15]	ITER
P_{fus} (MW)	150	225	500	180	180	500	410
S_{neut}(10^{19} #/s)	5.3	8.0	17.6	7.1	7.1	17.6	14.4
Major radius, R (m)	3.1	4.5	3.9	4.2	3.7	3.7	6.2
Aspect ratio, A	3.5	5.0	3.5	4.0	3.4	3.4	3.1
Elongation, κ	1.7	1.8	1.7	1.7	1.7	1.7	1.8
Current, I (MA)	7.0	6.0	8.0	7.2	8.3	10.0	15.0
Magnetic field, B (T)	6.1	7.5	5.7	6.3	5.7	5.9	5.3
Safety factor, q_{95}	3.0	3.1	3.0	3.0	3.0	4.0	
H_{IPB98}(y,2)	1.1	1.0	1.5	1.0	1.0	1.06	1.0
Normalized beta, β_N	2.5	2.5	4.0	2.0	2.0	2.85	1.8
Plasma Mult., Q_p	2.0	2.0	4.0	2.9	3.1	5.1	10
γ_{cd} (10^{-20} A/Wm^2)	0.37	0.23	0.04	0.5	0.61	0.58	
Bootstrap current, f_{bs}	0.40	0.50	≥0.90	0.35	0.31	0.26	
NeutronΓ_n (MW/m^2)	0.8	0.8	1.7	0.9	0.6	1.8	0.5
FW q_{fw} MW/m^2)	0.34	0.29	0.5	0.23	0.23	0.65	0.15
Availability (%)	≥ 50	≥ 50	≥ 50	≥ 50	≥ 50	≥50	

The requirements on β_N and confinement are within the range routinely achieved in present experiments (except for FTWR-AT and GCFTR-3), and the requirements on β_N, confinement, energy amplification Q_p, and fusion power level are at or below the ITER level. The requirement on the current-drive efficiency, after calculation of bootstrap current fraction using ITER scaling, is only somewhat beyond what has been achieved to date (γ_{CD} = 0.45 in JET and 0.35 in JT60-U). The ongoing worldwide tokamak program is addressing the current-drive/bootstrap current/steady-state physics issue. The current-drive efficiency/bootstrap fraction needed for FTWR/GCFTR is certainly within the range envisioned for Advanced Tokamak operation and may be achieved in ITER.

Although single numbers are shown for each parameter in Table IV, there is of course a broad range of values for these various parameters over which the design objectives can be met, as depicted in the operating space plots of Figs. 2 and 3 for the GCFTR designs.

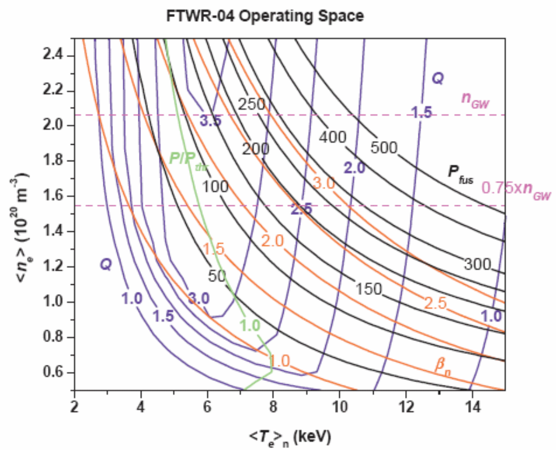

Figure 2:Operating space of the GCFTR at 7.2 MA [9].

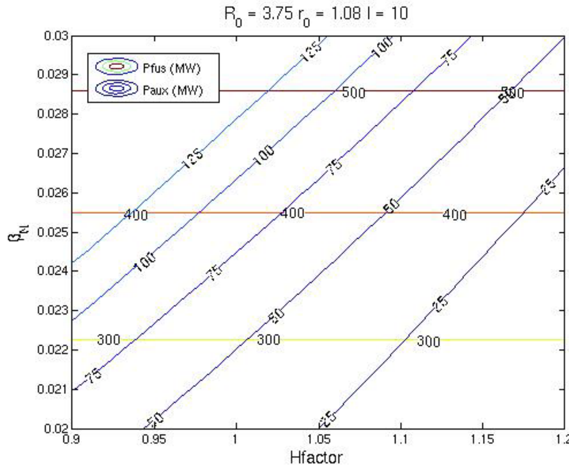

Figure 3: Operating space of GCFTR-3 at 10 MA[15,16] (Horizontal lines indicate P_{fus} and slanted lines P_{aux})

5. Neutron Source Technology for GCFTR-3[16]

The ITER divertor was adapted for helium coolant by having individual helium flow loops for the inner vertical, outer vertical and dome, but otherwise was just scaled down to the GCFTR dimensions with the same coolant channels. A 3D analysis of heat removal from a channel indicated incident heat fluxes up to 2 MW/m^2 could be removed with helium flow up to 143m/s without exceeding the maximum allowable temperature of 773 K in the copper block. A maximum of 10.6 MW pumping power was required to pump helium at 222 kg/s to remove 2 MW/m^2.

The ITER heating and current drive system was adapted to provide 100 MW of heating and to drive 7.5 MA of plasma current. Lower Hybrid (LH) was chosen as the reference system because of the superior current drive efficiency and the very constrained access requirements.

The TF and CS superconducting magnet systems for FTWR and GCFTR were directly adapted from the ITER cable-in-conduit Nb_3Sn conductor surrounded by an Incoloy 908 jacket and cooled by a central channel carrying super-cooled helium, with maximum fields of 11.8 and 13.5 T, respectively. The dimensions of the CS coil were constrained by the requirement to provide inductive startup (107 V-s for GCFTR-3) and to not exceed a maximum stress of 430 MPa set by matching ITER standards and Incoloy properties, based on the GCFTR structural fraction of 0.564. The dimensions of the 16 TF coils were set by conserving tensile stress calculated as for ITER, taking advantage of an Incoloy 908 jacket for support.

6. Component Lifetimes

The design lifetime of the FTWR and GCFTR neutron source is 40 years at 75% availability, or 30 EFPY. The superconducting magnets are shielded to reduce the fast neutron fluence to the superconductor and the dose to the insulators below their respective limits—10^{19} n/cm^2 fast neutron fluence for Nb_3Sn and 10^9 rads for organic insulators (10^{10} rads for ceramic insulators). The first-wall of the plasma chamber and the plasma-facing part of the divertor will accumulate fast neutron fluences of 7.5 and 5.8x10^{23} n/cm^2, respectively, over the 30 EFPY lifetime. The radiation damage limit of the ferritic or ODS steel first-wall structure is estimated at 1.5-3.0x10^{23} n/cm^2 , which implies that it will be necessary to replace the first- wall 2-4 times. The FTWR fuel cycle would accumulate a fast neutron fluence of 3.4x10^{23} n/cm^2 over a 5-batch residence time, which is at the upper limit of the estimated lifetime fluence for the ferritic or ODS steel cladding and assembly structure. The fuel would then be reprocessed, reclad, recycled and placed into a new structural assembly. The similar reprocessing fuel cycle for the GCFTR would accumulate a fast neutron fluence of 6.9x10^{22} n/cm^2 over a 8.2 year residence time, while the non-reprocessing GCFTR fuel cycle would accumulate up to 4.3x10^{23} n/cm^2, which is a major challenge for structural material and coated fuel particle development.

7. Requirements for Neutron Source and Electricity Production

The technical requirements for a tokamak fusion neutron source that would fulfill the transmutation mission are significantly less demanding than for an economically competitive tokamak electrical power reactor and somewhat less demanding than for a DEMO, as indicated in Table V.

Table V: TOKAMAK NEUTRON SOURCE, ELECTRIC POWER AND DEMO REQUIREMENTS

Parameter	ITER	Transmutation	ElectricPower[20]	DEMO[21]
Confinement $H_{IPB98}(y,2)$	1.0	1.0-1.1	1.5-2.0	1.5-2.0
Beta β_N	1.8	2.0-2.9	> 5.0	> 4.0
Power Amplification Q_p	5-10	3-5	> 25	> 10
Bootstrap Current Fraction f_{bs}		0.2-0.5	0.9	0.7
Neutron wall load (MW/m^2)	0.5	0.5-1.8	> 4.0	> 2.0
Fusion Power (MW)	410	200-500	3000	1000
Pulse length/duty factor	modest	long/steady-state	long/steady-state	long/steady-state
Availability (%)	<10	> 50	90	< 50

8. Conclusions

Sub-critical operation, with a neutron source, provides nuclear reactors with additional flexibility in achieving fuel cycles that better utilize fissionable material and that reduce long-lived transuranic isotopes in the material ultimately deposited in high-level-waste repositories, thus for realizing the ultimate objective of closing the nuclear fuel cycle. A tokamak D-T fusion neutron source based on ITER physics and technology, and for which ITER operation would serve as a prototype, would meet the needs of such transmutation reactors, thus enabling fusion to contribute to solving the world's energy and environmental problems at a much earlier stage than would be possible with pure fusion electricity production.

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1. "First Phase P&T Systems Study: Status and Assessment Report on Actinide and Fission Product Partitioning and Transmutation", OECD/NEA, Paris (1999).
2. "Proc. 1st-5th NEA International Exchange Meetings", OECD/NEA, Paris (1990,92,94,96,98).
3. "Nuclear Wastes--Technologies for Separations and Transmutations", National Research Council, National Academy Press, Washington (1996).
4. "A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology", US Dept. Energy report DOE/RW-0519 (1999).
5. W. M. Stacey, "Capabilities of a DT Tokamak Fusion Neutron Source for Driving a Spent Nuclear Fuel Transmutation Reactor", *Nucl. Fusion, **41***, 135 (2001).
6. W. M. Stacey, J. Mandrekas, E. A. Hoffmann, et al., "A Fusion Transmutation of Waste Reactor", *Fusion Sci. Technol., **41***, 116 (2002).
7. A. N. Mauer, W. M. Stacey, J. Mandrekas and E. A. Hoffman, "A Superconducting Fusion Transmutation of Waste Reactor", *Fusion Sci. Technol.,* **45**, 55 (2004).
8. J. Mandrekas, L. A. Cottrill, G. C. Hahn and W. M. Stacey, "An Advanced Tokamak Neutron Source for a Fusion Transmutation of Waste Reactor", Georgia Tech report GTFR-167 (2003).
9. W. M. Stacey, et al., "A Sub-Critical, Gas-Cooled Fast Transmutation Reactor (GCFTR) with a Fusion Neutron Source", *Nucl. Technol.*, **150**, 162 (2005).
10. W. M. Stacey, et al., "A Sub-Critical, He-Cooled, Fast Reactor for the Transmutation of Spent Nuclear Fuel", *Nucl. Technol.*, (Oct.,2006).
11. E. A. Hoffmann and W. M. Stacey, "Comparative Fuel Cycle Analysis of Critical and Subcritical Fast Reactor Transmutation Systems", *Nuclear Technol.*, **144**, 83 (2003).
12. W.M. Stacey, J. Mandrekas and E.A. Hoffman, "Sub-Critical Transmutation Reactors with Tokamak Fusion Neutron Sources", *Fusion Sci. Techn.*, **47**, 1210 (2005).
13. E. A. Hoffman and W. M. Stacey, "Nuclear Design and Analysis of the Fusion Transmutation of Waste Reactor", *Fusion Sci. Technol.*, **45**, 51 (2004).
14. J. W. Maddox and W. M. Stacey, "Fuel Cycle Analysis of a Sub-Critical , Fast, He-Cooled Transmutation Reactor with a Fusion Neutron Source", *Nucl. Technol.*, to be published (2006).
15. W. M. Stacey, et al., "Advances in the Sub-Critical, Gas-Cooled, Fast Transmutation Reactor Concept", *Nucl. Technol.*, submitted (2006).
16. J.-P. Floyd, J. C. Schultz, B. H. Shrader, et al., "Tokamak Fusion Neutron Source for a Fast Transmutation Reactor", *Fusion Sci. Technol*., submitted (2006).
17. R. N. Hill and H. S. Khahil, "Physics Studies for Sodium Cooled ATW Blanket", Argonne National Lab report ANL/RAE/CP-105355 (2001).
18. J.D. Galambos, L.J. Perkins, S.W. Haney, J. Mandrekas, "Commercial tokamak reactor potential with advanced tokamak operation," Nucl. Fusion, 35, 551 (1995).
19. W. M. Stacey, *"Fusion Plasma Physics"*, Wiley-VCH, Berlin (2005), chp 19.
20. ARIES web site http://www-ferp.ucsd.edu/ARIES/
21. W. M. Stacey, "Tokamak Demonstration Reactors", *Nucl. Fusion,* **35**, 1369 (1995).