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PROSPECTS FOR TOKAMAK FUSION REACTORS*

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MASTER

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PROSPECTS FOR TOKAMAK FUSION REACTORS

PERSPECTIVES D'AVENIR DES RÉACTEURS À FUSION DÈ TYPE TOKAMAK

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1. Introduction

1. Introduction

This paper first reviews briefly the status and plans for research in magnetic fusion energy and discusses the prospects for the tokamak magnetic configuration to be the basis for a fusion power plant. Good progress has been made in achieving fusion reactor–level, deuterium-tritium (D-T) plasmas with the production of significant fusion power in the Joint European Torus (up to 2 MW)[1] and the Tokamak Fusion Test Reactor (up to 10 MW)[2] tokamaks. Advances on the technologies of heating, fueling, diagnostics, and materials supported these achievements.

The successes have led to the initiation of the design phases of two tokamaks, the International Thermonuclear Experimental Reactor (ITER)[3,4] and the U. S. Toroidal Physics Experiment (TPX).[5] ITER will demonstrate the controlled ignition and extended burn of D-T plasmas with steady state as an ultimate goal. ITER will further demonstrate technologies essential to a power plant in an integrated system and perform integrated testing of the high heat flux and nuclear components required to use fusion energy for practical purposes. TPX will complement ITER by testing advanced modes of steady-state plasma operation that, coupled with the developments in ITER, will lead to an optimized demonstration power plant.

We will discuss only the use of D-T fuel, for which the fusion reaction is

$$D + T \longrightarrow {}^{4}He\ (3.52\ MeV) + n\ (14.06\ MeV). \qquad (1)$$

Consequences of this reaction are the need to remove helium "ash" to prevent dilution of the D-T fuel and the need to handle 14 MeV neutrons, which both induce radioactivity in the structure and cause damage. Deuterium is abundant in water, but tritium must be produced in the power plant. The plasma will be surrounded by a blanket containing lithium:

$$\begin{aligned} {}^{6}Li + n &\longrightarrow {}^{4}He + T + 4.80\ MeV \\ {}^{7}Li + n &\longrightarrow {}^{4}He + T + n - 2.47\ MeV. \end{aligned} \qquad (2)$$

The evaluation of other fusion cycles such as D-^{3}He is beyond the scope of this paper.

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Studies of the environmental, safety, health, and cost aspects of fusion power plants, such as the Committee on Environment, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM),[6] have been made. They show that a magnetic fusion power plant can have very good features, in this regard, provided that the materials subjected to the 14 MeV neutron of the D-T reaction have low induced activity and can withstand 15 or more MW years m^{-2} of 14 MeV neutron fluence. Consequently, another major aspect of fusion development is materials research, and the design of an intense 14 MeV neutron source, the International Fusion Materials Irradiation Facility (IFMIF),[7] is under way.

Finally, this paper investigates the consequences of using developments of ITER and TPX and the materials program in making a magnetic fusion power plant. It provides a comparison with the present best experience for pressurized water reactors[8] and with the projected best experience for fission reactors.[9]

2. Tokamaks
2. Les tokamaks

The tokamak configuration has received the highest funding in magnetic fusion; consequently, it is the most studied, the most developed, and the most credible approach, at present, to making a fusion power plant. A cutaway drawing of a reference tokamak reactor is shown in Fig. 1. The tokamak offers good solutions to many of the main requirements that confront a power plant designer. These requirements are as follows:

- having a low transport rate of heat and of the D-T fuel;
- having a high enough transport rate of helium ash to minimize dilution of the fuel;
- providing a divertor system to remove helium efficiently and minimize the generation and input of wall-generated impurities;
- operating in steady state with no plasma disruptions and with a low level of recirculating power to sustain the plasma;
- having a cost-effective "simple" magnetic coil system with, ideally, no trapped coils and good access for maintenance and repair; and
- having a high enough plasma pressure that, with the simple coils, the system has a high enough power density to approach the ideal cost-of-electricity (COE) limit.

Beta is defined as the ratio of plasma pressure to magnetic pressure. A convenient estimate of the maximum limit is given by

$$\text{beta limit} \sim \beta_N \frac{I(MA)}{B(T)a(m)} \%, \tag{3}$$

where (I) is the plasma current, (B) is the toroidal magnetic field, and (a) is the plasma minor radius in the median plane. For a tokamak , typically, $\beta_N \sim 3$ and < 6.

The tokamak is least satisfactory in regard to steady-state operation since, in its basic form, the current is driven by a transformer that limits the pulse duration. For steady-state operation, somewhat complex systems are required to drive the plasma current, and present devices can suffer loss of control of the plasma called a disruption. Good progress has been made in developing noninductive current drive systems, in minimizing the need for current drive, and in characterizing and avoiding disruptions. Operating modes have been found in which the current that is self-driven by the plasma, the bootstrap current, is 70% or more. Such levels of bootstrap current reduce the need for external current drive. In addition, the beta of a conventional tokamak is relatively low ~ 5%, and obtaining reactor grade plasma requires relatively complex and high field ($\gtrsim$ 12T) superconducting coils. The present and optimized tokamak contrasted with an "ideal system" may be postulated,[10,11,12] in which the coils are a very small part of the cost, and the cost stems primarily from the inescapable components: minimal plasma heating (and sustaining system), tritium breeding blanket, shield, particle input, removal and treatment system, heat transfer system, generators, buildings, and balance of plant.

No present system meets the ideal standards; however, toroidal systems, of which the tokamak is the most successful, contain among them the elements required. A discussion of the broader toroidal program, including such devices as the very low-aspect ratio tokamak (spherical torus), stellarator, reversed-field pinch, spheromak, and field-reversed configuration is beyond the scope of this paper. For a recent review, see "The Physics of Magnetic Fusion Reactors."[13]

3. ITER and TPX
3. ITER et TPX

Success in the tokamak program has led to the initiation of the ITER project.[3,4] The conceptual design activity (CDA)[3] was completed in 1989. The ITER engineering design activity (EDA)[4] is under way as a four-party venture — comprising the European Economic Community, Japan, Russia, and the United States — under the auspices of the International Atomic Energy Agency (see Figure 2). The ITER program forces the fusion community to face up to the realities of magnetic fusion with an extended pulse (steady-state) D-T burning plasma. The studies highlight the problem areas and show clearly where the tokamak and toroidal systems, in general, must improve in regard to the requirements in Section 2.

The ITER concept is based on relatively conservative physics assumptions and is designed with a large margin in performance to ensure that it can operate with an ignited, self-sustained plasma using a transformer to drive the plasma current for at least 15 minutes. Key drivers of the size and cost of ITER are the provision of the massive transformer and the assumption of a need to handle a poor rejection rate of helium ash. In addition, tokamak operating modes, which require less plasma current and reduce the transformer and supplementary, noninductive current drive, have been achieved for short pulses. These modes offer the potential for a much improved power plant, as has been developed in the Advanced Reactor Innovation and Evaluations Studies (ARIES).[14]

The TPX is a national effort involving laboratories, universities, and industries in the United States. Both ITER and TPX will develop impurity minimization techniques to reduce helium ash accumulation and wall-generated impurities and allow more fusion power for a given beta. The TPX will incorporate these advanced features and test them for plasma durations of 15 minutes to steady state. Some improvements in operation demonstrated in TPX may be incorporated in ITER and allow effective operation in steady state at reduced plasma current. The primary characteristics of ITER and TPX are given in Table 1. It is important to note that although the nominal ITER fusion power is 1500 MW, it can produce, including the exothermic blanket gain, more than 5000 MW of thermal power near the beta limit with good impurity control.

Table 1 Primary characteristics of ITER and TPX
Tableau 1 Les caractéristiques principales de ITER et TPX

	ITER	TPX
Major radius (m)	8.10	2.25
Minor radius (m)	3.00	0.50
Elongation	1.6	2.0
Toroidal field (T)	5.7	4.0
Plasma current (MA)	24.0	2.0
Pulse length (s)	$\gtrsim$ 1000 (∞)	1000 (∞)
Fuel	D-T	D-D
Breeding blanket	Phase 2	No
Nominal fusion power (MW)	1500	

4. Cost of electricity
4. Le coût de l'électricité

The model used to calculate the COE is that derived from generic reactor studies[8] and incorporated in the SUPERCODE.[15] The COE is determined from the formula

$$\text{COE} \cong \frac{\text{Fixed charge rate x Capital cost + O\&M + Fuel}}{\text{Availability x Hours in a year x Net electric power}} + \text{Decommissioning.} \quad (4)$$

The fixed charge rate is the annual repayment (mortgage cost) on the money borrowed during construction. In constant dollars, the rate is $\simeq 0.1$. The capital cost includes interest charges during construction. Operations and maintenance (O&M) costs are expected to be similar to those of fission plants because a similar number of required plant personnel are expected, though a different mix of skills is required. Fuel costs include deuterium plus the annualized cost of the lithium breeding blankets used during the life of the plant. Decommissioning costs of 0.5 mill/kWh are assessed much in the way fission systems are.

Table 2 Assumptions used in the plant power balance and COE calculation
Tableau 2 Les hypothèses utilisées pour la balance energétique de la centrale électrique et pour les calculs du CDE

Plant Power Balance	
Thermal to electric efficiency	0.45[a]
Percentage of plasma thermal power converted to electricity	70%
Blanket energy gain	0.30
Current drive power efficiency, wall plug to plasma efficiency	72%
Costing Assumptions	
Construction time (year)	6
Plant life (year)	30
Average capacity factor	75%
Indirect + contingency cost factor	46%[b]
Fixed charge rate[c] (*FCR0*)	0.0966
Effective cost of money (year^{-1})[d]	0.1135
Inflation rate (year^{-1})	0.05
Direct cost	10th of-a-kind[e]

[a]Assumes a high-temperature helium cooling system.
[b]Taken from the ITER CDA[3] for indirect + contingency cost.
[c]Constant dollar.
[d]We input the fixed charge rate independent from this value. The cost of money is used only for estimating the capitalization factor.
[e]A 20% cost reduction is applied to the tokamak reactor plant equipment (corresponding to a 94% learning ratio for each doubling of the number of units).

The availability (capacity factor at full power) is the most uncertain quantity because of the lack of data on component and system reliability and maintenance requirements. A goal of 0.75 is set. The net electric power is given by

$$P_e = [0.14\, P_f + 0.8(1 + g_n)P_f]\eta_e - P_{Bop} - P_{aux}. \quad (5)$$

P_f is the fusion power, g_n is the exothermic blanket gain, and η_e is the effective thermo-electric conversion efficiency. P_{Bop} is the power used in the balance of plant. P_{aux} is the auxiliary power (MW_e) used to sustain the plasma configuration and run the fusion reactor. The 0.14 factor assumes that 70% of the charged fusion power will be converted to useful heat because it is unlikely that all surfaces receiving heat will be able to be maintained at high temperatures.

Table 3 ITER-like reactor parameters
Tableau 3 Les paramètres pour réacteurs de type ITER

	ITER - like physics β_N < 3.5 κ=1.6		**Advanced physics** β_N < 6 κ= 2.0 **90% BS fraction**
	1200 MW(e)	1800 MW(e)	2000 MW(e)
COE (mills/kWh)	132	102	63
Overnight capital cost (1993 billion$)	8.21	9.41	5.95
$f_{recirculate}$ (%)	28.5	25.6	11.7
Core mass (ktonnes)	43.9	49.1	24.4
MPD (kW_e/tonne)	27.3	36.7	79.6
Major radius (m)	8.1	8.1	6.50
Aspect ratio	2.55	2.39	1.95
Plasma current (MA)	22.0	26.3	13.3
Field on axis (T)	4.83	4.83	4.53
$B_{max-TF\ coil}$ (T)	11.4	12.3	11.3
q_{95}	3.0	3.0	4.0
Fusion power (MW)	2960	4290	4120
Injection power (MW)	216	279	32
Bootstrap fraction	0.37	0.36	0.90
Plasma energy gain, *Q*	13.7	15.4	131.0
ITER-89 P *H* factor	1.92	1.76	2.22
Total beta (%)	5.10	5.60	9.01
Neutron wall load (MW/m^2)	1.72	2.32	3.48

A self-consistent reactor design is obtained using the SUPERCODE.[15] The SUPERCODE systems code includes tokamak physics and engineering models coupled through an optimization driver. In these calculations we use global plasma physics modeling typical of reactor studies and engineering/costing analyses that were developed to model the ITER-CDA device. We have also incorporated standard power reactor models[8,10] and for all cases here use the minimum COE as the optimization figure-of-merit. Table 2 lists some primary reactor modeling assumptions. The cost models are different from those used in the ARIES study[14] because we normalize our tokamak-related cost scalings with the ITER-CDA design. The remaining plant cost scalings are similar to those in ARIES. For all cases shown, we employ global, volume-averaged transport models with profiles adjusted to match parabolic shapes for temperature and density. We use a fixed-boundary magnetohydrodynamic (MHD) equilibrium calculation that provides the relationship among the plasma current, the current profile, and the plasma geometry. The physics modeling includes constraints for impurity levels, power balance, beta limit, MHD requirements, current-drive, alpha particle confinement, and inductive volt-seconds. The engineering models include constraints for toroidal field (TF) coils, poloidal field coils, TF coil ripple, shielding, divertor build, injection power, and neutron wall loading.[11] The primary difference between these modeling assumptions and those of Ref. 11\ is the use of a lower helium ash concentration (5%) and slightly higher elongation (k = 2 at the 95% surface) for advances beyond the basic ITER layout. The blanket and first wall have a vanadium structure and a liquid lithium coolant/breeder.[16] The parameters of reference reactor designs are given in Table 3.

4.1 Comparison of fusion and fission COE
4.1 Comparaison du CDE pour la fusion et la fission

Performance and costs of fission reactors are analyzed regularly. The present best experience for ~1200 $MW_{(e)}$ pressurized-water reactors (PWRs) has been assessed by Delene,[8] and projections of best future performance for ~600 $MW_{(e)}$ reactors have been made by the U.S. Council for Energy Awareness.[9] Table 4 also provides a comparison of projected fusion costs with the fission experience and projections.

Table 4 Comparison of fission and fusion
Tableau 4 Comparaison pour la fusion et la fission

FY 1993 $ Fixed charge rate = 0.097. F_{AV} = mills/kWh				
	Capital	O&M	Fuel + Decom.	Total
ITER-1200[a]	116	9.5	6.5	132
ITER-1800[a]	88	8	6	102
ITER-2000 Advanced[a,b,c]	50.5	7.5	5	63
PWR-best experienced[d]	42.5	10	8	60.5
Fission-projected best[e]	28.5	9.5	8	46
Fusion base 2000[a,f]	≲28	≲7	~5	≲40

[a]Six years of construction time — basic ITER (K = 1.6, etc.), tenth of a kind costs.
[b]H-mode factor 2, β_N 6, 5% helium, 90% bootstrap current, 20% cost reduction for fusion-related items.
[c]COE scales roughly as $P_e^{-0.5}$.
[d]J. Delene, 1990, 1200-$MW_{(e)}$, 8-year construction lead time.
[e]U.S. Council for Energy Awareness,[9] 1992, 600-$MW_{(e)}$, 5-year construction time, optimistic assumptions, and cheap uranium.
[f]Fusion base means all components except magnet systems.

The ITER-1200 is a 1200-$MW_{(e)}$ fusion reactor based directly on an ITER-like design with an intermediate fusion power run at the beta limit of β_N = 3.5% m-T/MA. The ITER-1800 is a similar design run at the beta limit. Increased costs for handling the higher power and more frequent component replacement are included. The ITER-2000 Advanced is a design made smaller through the use of advanced tokamak features and incorporation of 20% lower unit costs. The fusion base reactor is a D-T system at 2000 $MW_{(e)}$ stripped to the minimum of components, that is, no magnets, and ignited. This minimal system is shown to indicate those when the fusion-specific items are eliminated, projected costs are similar to that of conventional power sources with inexpensive heat sources and fuel. Thus, even the ITER-2000 case has only ~ 50% higher COE than the ideal minimal possible COE for a fusion device.

It can be seen that advanced tokamak reactors can be competitive, though further gains will be needed for them to compete with the projected best fission systems. However, they would be of larger unit size than the fission systems, as discussed by Dolan.[17] Further, this analysis takes no account of the potential advantage of fusion reactors in safety and through the use of low activation materials leading to a much lower radioactive lifetime and waste impact.

5. Materials and breeding blankets
5. Les matériaux et les parois génératrices

The ESECOM study[6] investigated the environmental, safety, and economic aspects of magnetic fusion energy. It compared a number of reference fusion power plants with the best existing and some future fission plants. Among the fusion plants studied were a number of tokamaks, distinguished mainly by different approaches to the blanket, structure, and cooling.

- V-Li/Tok had a vanadium-alloy structure with a liquid lithium coolant/tritium breeder.
- RAF-He/Tok had a reduced activation ferritic steel structure, a helium coolant, and a Li_2O solid breeder.
- SiC-He/Tok had silicon carbide composite structure, a helium coolant, and a Li_2O solid breeder.

It was assumed that each plant would operate for 30 full-power operating years and that the material facing the plasma (first wall) and the breeding blanket behind it would have a lifetime of 20 MW years/m^2 of 14 MeV neutron fluence. With a typical neutron flux of 5 MW/m^2 at 75% capacity factor, there would be a blanket change-out approximately every 5 years. From an economic point of view, subject to the performance and costing assumptions, the fusion plants had projected costs comparable to those of similar output fission plants.

The major advantage of the fusion plants over fission systems for comparable performance and cost lies in the safety and environmental areas. The materials discussed above suffer relatively low induced activity and a much more rapid decay of activity than the materials in fission power plants, and there are no actinides in the fusion case. The level of activity as a function of time for the materials proposal for fusion plants is compared with a fission example in Figure 3. From a radioactive waste point of view, fusion is superior to fission by 100 times. In addition, routine emissions of radioactive materials are projected to be better than emissions for fission. As to the issue of proliferation, although the tritium will require careful accounting, the introduction of fertile materials should be more difficult to do because they should not be on-site, and they would be easier to detect than in the fission plant case.

So fusion can be an attractive power source provided the low activation materials can be developed.[6,18] The challenge lies in the demands placed upon the first wall and blanket structure. This material is subjected to an intense flux of 14 MeV neutrons (~5 MW/m^2) and must conduct, at reasonable temperatures, a somewhat smaller heat flux. For economic reasons these components must withstand ~20 MW years/m^{-2} of neutron fluence. This fluence will cause ~200 displacements per atom in the material and produce helium and hydrogen in the structure. The gases can collect in the structure and form bubbles, which lead to swelling. These key properties must be retained in this environment:

- thermal conductivity,
- low swelling,
- strength,
- low ductile-to-brittle transition temperature, and

- chemical compatibility with the coolant and breeder.

In addition, they and components farther away from the plasma should have low enough activation to satisfy safety and environmental requirements such as acceptable afterheat from induced radioactive decay, and rapid decay of activation.

Elements with good or acceptable activation properties include, lithium, beryllium, carbon, silicon, aluminum, titanium, vanadium, chromium, iron, tantalum, and tungsten. Elements which suffer bad activation include copper, molybdenum, nitrogen, niobium, and nickel. Trace amounts of bad elements will set the lower bound of activation level for good materials. The vanadium alloy/liquid-lithium first wall and blanket design used in the costing analysis for ITER/TPX-derived reactors was developed in a study for ITER.[17]

To date, qualification and down-selection of materials has been achieved by irradiation in fission reactors, by bombardment with high energy ions, and by the use of various techniques to produce helium in the material. New facilities are required to qualify the materials. A "14MeV" small test volume, intense neutron source is being developed, under the auspices of the International Energy Agency, based on accelerated deuterium ions impinging on a flowing lithium target (IFMIF). A larger volume neutron source is required for testing large blanket elements. This is a role for both ITER and a smaller dedicated facility.

Substantial progress has been made in the last two decades in understanding the neutron damage problems and in focusing on a few candidate materials. Most research is now concentrated on vanadium alloys, ferritic (martensitic) steels, and silicon carbide. Beryllium, carbon composites, and tungsten are being considered as plasma facing materials. Encouraging results have been obtained from fusion reactor irradiation of vanadium (chromium + titanium) alloys.[18]

6. Conclusion
6. Conclusions

The tokamak is the most developed magnetic fusion concept. It has the potential through the ITER, TPX, and other parallel programs to lead to an economic magnetic fusion power plant near the middle of the 21st century. There is an economy of scale, and this route favors relatively large plant size, ~2000 $MW_{(e)}$. Other toroidal concepts offer improvements in a number of key areas, and some evolved concept may ultimately make the best power plant. The use of low activation materials is essential in making an acceptable, attractive power plant.

Good progress is being made in all aspects of fusion, thanks to extensive international collaboration. A vigorous program must be maintained if fusion energy is to be available in the middle of the 21st century.

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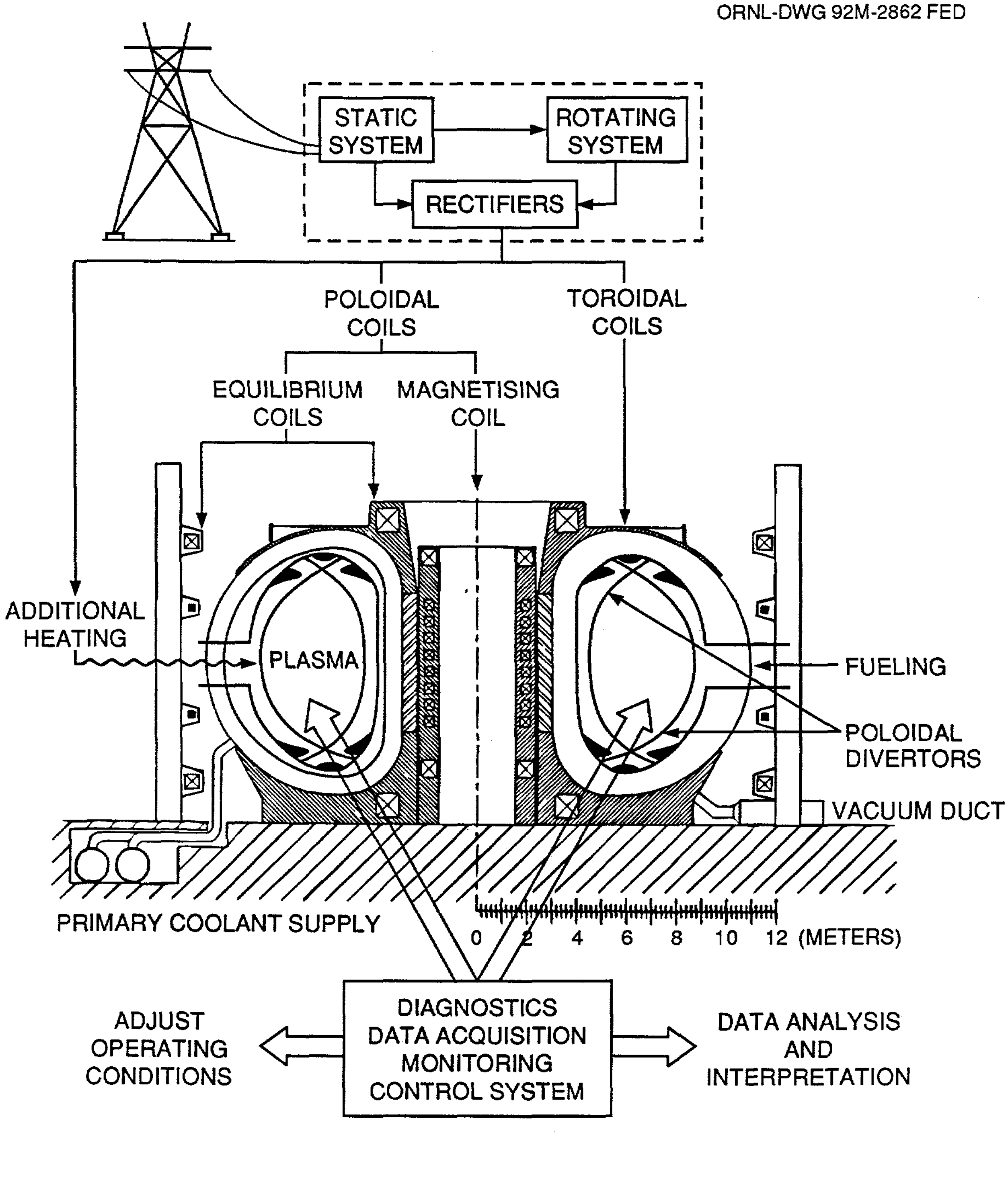


Fig. 1 Tokamak Reactor Configuration
Fig. 1 Configuration d'un réacteur de type tokamak

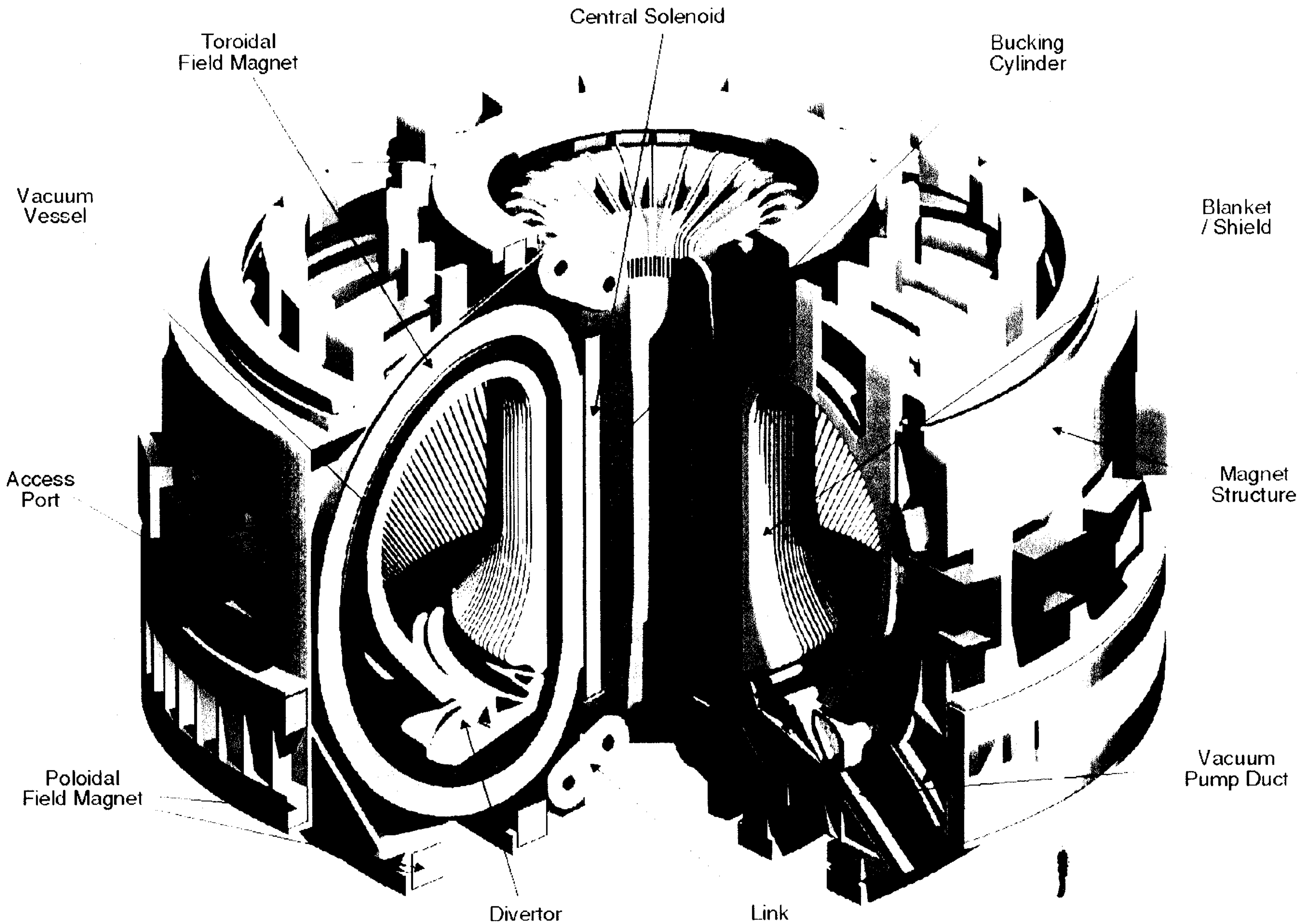
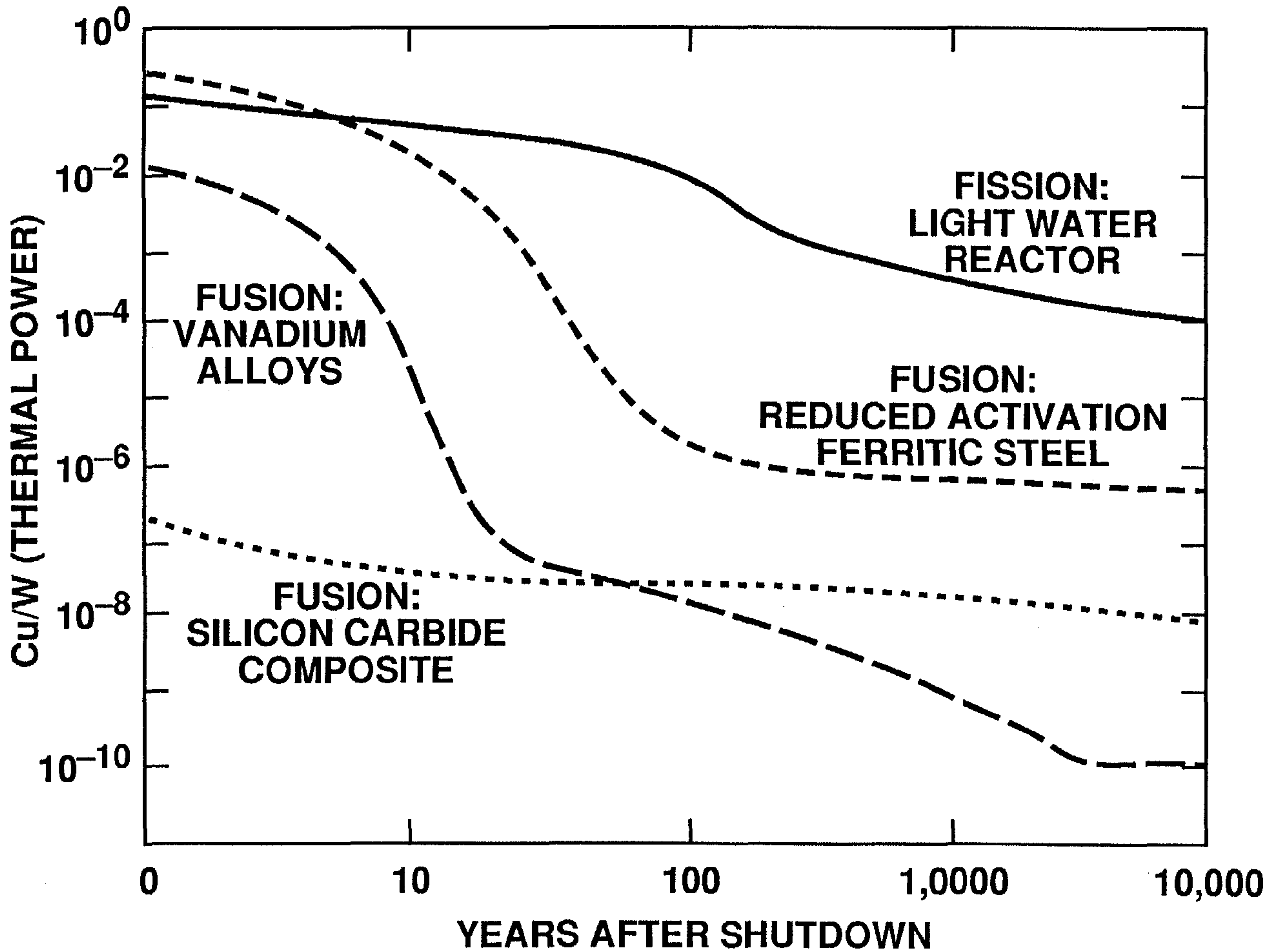


Fig. 2 ITER Configuration
Fig. 2 La configuration ITER

Fig. 3 Comparison of fission and fusion power plant radioactivity after shutdown

Fig. 3 Comparaison de la radioactivité après termination pour les centrales génératrices par fission et par fusion



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16TH CONGRESS OF THE WORLD ENERGY COUNCIL

Summary

PROSPECTS FOR TOKAMAK FUSION REACTORS
PERSPECTIVES D'AVENIR DES RÉACTEURS À FUSION DÈ TYPE TOKAMAK

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SUMMARY

This paper reviews the status and plans for research in magnetic fusion energy and discusses the prospects for the tokamak magnetic configuration to be the basis for a fusion power plant. Recent successes have led to the initiation of two tokamaks: the International Thermonuclear Experimental Reactor (ITER) and the U.S. Toroidal Physics Experiment (TPX). The engineering design phase of ITER is well under way as a four-party venture — comprising the European Economic Community, Japan, Russia, and the United States — under the auspices of the International Atomic Energy Agency. Completion of the design is expected in 1998/99 and construction is estimated to last 7 years. ITER will demonstrate the extended burn of a fusion plasma at the 1500 MW level. ITER will further demonstrate technologies in an integrated system and perform testing of the high heat flux and nuclear components required to use fusion energy for practical purposes. TPX will demonstrate improved plasma operating approaches. These approaches, coupled with developments in ITER and other areas, notably materials, should lead to a continuously operating tokamak power plant . Such a plant should have the potential for economic competitiveness with present fission power plants operated with a similar capacity factor. The costing methodology is based upon one used in assessing fission reactor economics. The costing of a fusion power plant assumes modest improvements over the ITER and TPX experience and the results are consistent with other recent tokamak power plant studies. The potential environmental, safety, and health advantages of fusion are an important factor in the acceptance of fusion energy. The ability to provide materials which can withstand the 14 MeV fusion neutrons with low induced radioactivity is very important to the viability of a fusion power plant. Materials development plans are discussed briefly. This paper concludes that there is the potential, through the ITER, TPX, and other parallel programs, notably for low activation materials, to develop an economic magnetic fusion power plant in the middle of the 21st century. There is an economy of scale and this route favors relatively large plant size ~ 2000 MW(e).

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PERSPECTIVES D'AVENIR DES RÉACTEURS À FUSION DE TYPE TOKAMAK

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Ce manuscript passe en revue le statut et les plans de la recherche en énergie par fusion magnétique et traite des perspectives d'avenir de la configuration magnétique de type tokamak en tant que base pour une centrale génératrice par fusion. Les succès récents ont donné lieu aux commencements de deux tokamaks: l'International Thermonuclear Experimental Reactor (ITER) et le Toroidal Physics Experiment (TPX) aux Etats Unis. La phase d'études de génie pour ITER est bien avancée au sein d'une entreprise quadripartite - comprenant l'Union Européenne, le Japon, la Russie, et les États Unis - sous les auspices de l'Agence Internationale pour l'Energie Atomique (IAEA). L' achèvement est attendu pour 1988/89 et la construction devrait durer 7 ans. ITER demontrera la combustion soutenue d'un plasma à fusion à un niveau de 1500MW. ITER demontrera aussi des technologies dans un systeme intégré et accomplira des essais de flux de chaleur élevés et de composantes nucléaires nécéssaires pour l'utilisation de l'énergie par fusion à des fins pratiques. TPX démontrera des approches améliorées d'opérations du plasma. Ces approches, liées aux développements dans le cadre d'ITER et dans d'autres domaines, devraient éventuellement résulter en une centrale génératrice de type tokamak à opération continue. Une telle centrale devrait avoir le potentiel d'être compétitive du point de vue économique avec les centrales par fission actuelles operant avec un facteur de capacité comparable. La méthodologie du coût est basée sur celle utilisée pour évaluer la rentabilité des réacteurs par fission. L'évaluation des coûts d'une centrale génératrice par fusion suppose de modestes améliorations par rapport à ITER et TPX et ses résultats sont compatibles avec d'autres études récentes de centrales génératrices de type tokamak. Les avantages en puissance de la fusion ayant trait à l'environnement, la sécurité et la santé sont un des facteurs importants pour l'acceuil favorable de l'énergie par fusion. La capacité de produire des materiaux capables de résister aux neutrons de fusion à 14MeV avec une radioactivité induite faible est d'une importance primordiale pour les centrales génératrices par fusion. Les projets de développement de tels materiaux sont brièvement discutés. Ce manuscript amène à la conclusion que le potentiel existe, par le biais d'ITER, de TPX et d'autres programmes parallèles, notamment pour les matériaux à faible taux d'activation, de déveloper une centrale génératrice par fusion magnétique économique pour le milieu du 21ième siècle. Il éxiste une économie d'échelle et cette avenue favorise une centrale de capacité relativement importante ~ 2000 MW (e).