Materials for the fusion reactor

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Abstract

Development of fusion technology is a long-term objective of the European Community, covering the construction at ten-year intervals of an experimental reactor, a demonstration reactor, and lastly the commercial reactor, based on magnetic confinement of a plasma of deuterium and tritium. Problems relating to materials involved in the programme are analysed with special reference to the reactor structures most directly exposed to the actions of the plasma and neutron flux. For the experimental reactor, in which the most complex problem concerns the interactions of such structures with the plasma, the possible solutions are necessarily limited to a few steels currently used in nuclear engineering. For subsequent reactors the emphasis is on resistance to neutron damage and reduction of induced radioactivity. In that context steels and vanadium alloys with a highly controlled composition in regard to the presence of a number of elements are being studied. Development of such materials could allow exploitation of this inexhaustible energy source with extremely low environmental costs.

Riassunto

Lo sviluppo della Tecnologia della Fusione è un obiettivo a lungo termine della Comunità Europea. Tale sviluppo prevede la costruzione a scadenza decennale di un reattore sperimentale, di un reattore dimostrativo ed infine del reattore commerciale, basati sul confinamento magnetico di un plasma di deuterio e trizio. I problemi di materiali che tale programma comporta sono analizzati con particolare riferimento alle strutture del reattore più direttamente esposte all'azione del plasma e del flusso neutronico. Per il reattore sperimentale, in cui il problema più complesso riguarda l'interazione di tali strutture con il plasma, le possibili soluzioni sono necessariamente limitate ad alcuni acciai attualmente impiegati nella tecnologia nucleare. Per i reattori successivi l'accento è posto sulla resistenza al danneggiamento neutronico e sulla riduzione della radioattività indotta. In tale ottica vengono studiati acciai e leghe di vanadio a composizione estremamente controllata per quanto riguarda la presenza di alcuni elementi. Lo sviluppo di tali materiali potrebbe consentire lo sfruttamento di questa fonte inesauribile di energia a costi ambientali estremamente ridotti.

Introduction

The present crisis of nuclear fission energy has turned the hopes of the general public and the attention of researchers to nuclear fusion energy. Europe is playing an active part in developing this new technology and now, with the creation of JET *, is in the forefront of research into methods of magnetic plasma confinement.

The European fusion technology programme is aimed at creating a line of commercial reactors through a series of intermediate stages ranging from plasma physics machines like JET itself to IGNITOR **, for whose construction Italy recently became the organizer, and from an experimental reactor like NET *** to a demonstration reactor.

Each of these intermediate projects has a specific objective with concomitant design and operating characteristics that may be very diverse, as indicated by Table 1, which lists some significant parameters for them. For each of these projects a problem of materials has arisen, is arising, or will arise. One therefore cannot talk of developing materials for fusion technology in general terms, but reference must be made to a specific project, because the solutions adopted in one case will not necessarily be transferable to the next design.

The purpose of this paper is to examine the problems of the materials needed for developing this new technology and to say what solutions are currently under study for creating the experimental reactor (Fig. 1) in the mid term and the commercial one in the long term. Our analysis will be limited to the structural materials of the reactor components directly facing the plasma, which will mainly determine operating capacity, reliability, load factor and finally the actual reactor economics. Lastly, in regard to the commercial reactor's economics in a broad sense, we shall attempt to bring out the leading part that the selection of materials will play in fully realizing this new technology's great potentialities, above all in terms of safety and environmental protection (1).

Fuel cycle and operating conditions

The possibility of obtaining energy from a nuclear reaction is based on the lower mass per nucleon of elements of intermediate atomic number in comparison with lighter and heavier ones. Both fission, meaning the disintegration of a heavy nucleus into

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* JET (the Joint European Torus) has been operating at Culham, UK, since 1983. Built by a European team with funding from the Commission of the European Communities, it is currently the most advanced Tokamak (toroidal chamber magnetic confinement) machine for studying deuterium-tritium plasma in an ignition regime. Its objective is to achieve ignition by the early 1990s.

** IGNITOR is the project for a compact high-magnetic-field machine to be used as a complement to JET for investigating stability conditions for an ignited deuterium-tritium plasma.

*** NET (the Next European Torus) is the European project now under development at Garching, FRG, and Ispra, Italy, on the basis of results produced by JET. Its objective is to verify the maturity of all the technologies needed for commercial exploitation of fusion energy. NET should be completed by the beginning of the next century.

lighter nuclei, and fusion, the opposite process of condensation of two light nuclei into one heavier one, convert this excess mass into kinetic energy of the reaction products.

Whereas for the first process the choice of fuel is limited to the few heavy elements capable of giving rise to a chain reaction, for the second we can in principle choose from the more than a hundred known fusion reactions between light nuclei (from hydrogen isotopes to ^{11}B) and then determine the fusion reaction products and the energy production conditions.

The higher the charge, however, the more energy must be expended to overcome the electrostatic barrier that opposes fusion of the nuclei and the more difficult it will be to obtain a reaction with a positive energy balance, that is, ignition.

Whithin the bounds of current development, that objective can reasonably be thought attainable only via the reaction between deuterium and tritium, which produces 80% of its energy as kinetic energy of the neutrons and the remaining 20% as kinetic energy of alpha particles. The tritium required can be produced in the reactor itself by reacting the neutrons with a breeding material: lithium or its compounds.

Problems connected with tritium production are fully discussed in two exhaustive surveys in the recent literature (2,3).

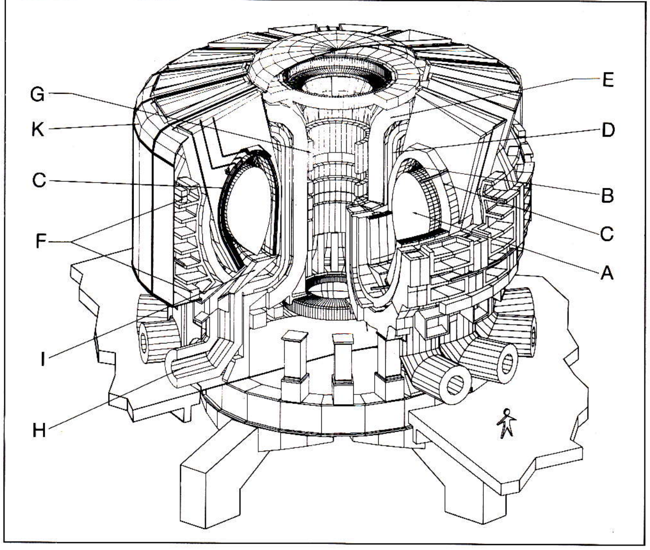

Fig. 1 - The NET experimental reactor, showing the toroidal chamber containing the plasma (A) and, continuing outwards, the assembly consisting of the first wall (B) and the impurities control system (I) forming the first solid barrier encountered by the energy flux from the plasma, then the blanket (C), which has the dual function of converting the neutrons' enery into heat and producing tritium through reactions with lithium; then there is the neutron shield (D), by which the toroidal field magnets (E) and vertical stabilizing magnets (F) needed for containment are protected from neutrons. The transformer coils (G) induce the plasma current needed for containment and ohmic heating of the plasma. Seen from the outside: vacuum system ducts (H) and cryostat (K).

TABLE 1 - Comparison of some design and operating parameters for JET and the experimental (NET), demonstration and commercial reactors

	JET	NET	Demonstration reactor	Commercial reactor
Minor radius of plasma, m	1.0	1.3	1.7	2.3
Major radius of plasma, m	3.1	5.2	7.3	9.4
Plasma current, MA	5.5	11	13	20
Pulse duration, s	3	200-1000	1000-5000	stable
Minimum dwell time, s	200-1500	70	50	—
Total thermal power, MW	—	750	2500	3600
Mean neutron wall load, MW/m^2	0.1	1.	1.5	1.8
Mean surface heat flux, MW/m^2	—	0.12	0.2-0.3	0.3-0.4
Load factor, %	—	25	50	80
Integrated wall load, MWa/m^2 *	10^{-5}	0.7	3.5	7-15
Number of plasma disruptions per cycle	0.1-0.5	10^{-2}-10^{-3}	10^{-4}	—
Number of cycles in lifetime	10^3-10^4	10^5	10^4-10^5	10^3-10^4

* MW annum/m^2

Recovery of neutron-associated energy causes induced radioactivity and damage through the interaction of neutrons with structural materials. Radioactive products require remote reactor maintenance, involve a moderate risk of release to the environment in the event of an incident, and create a problem of disposal of activated materials at the end of the reactor's life. Neutron damage modifies the material's physical and mechanical characteristics, crystallographic structure and chemical composition, reducing its limits of employment.

Recovery of energy associated with alpha particles, which reaches the first wall in the form of photons, ions and neutral atoms of high energy, in its turn creates a whole range of phenomena that are named plasma/wall interaction. Both the neutron flux and the flux carrying the remaining 20% of the energy produced are pulsed, with a pulse duration of a feu seconds in JET, some minutes or tens of minutes in NET, and possibly many hours in the commercial reactor if, as is hoped, we succeed in making the current circulate in the plasma with non-inductive methods.

Neutron damage

Neutron damage phenomena have long been studied in connection with the development of fission reactors. Swelling, irradiation-assisted creep, hardening and embrittlement are therefore quite well known phenomena. What is peculiar to fusion is the neutrons' energy spectrum, which extends up to 14 MeV. The neutrons' high energy provokes a much more abundant production of solid and gaseous transmutants than in fission reactors. Data on the variation of composition in a structural material according to irradiation can be found in Ref. 4. In particular, the ratio of helium produced per unit of neutron damage, which is 0.1 ppm per dpa (displacement per atom) in a fast reactor, rises to 15 ppm/dpa in the fusion reactor in an austenitic steel. The effect of these transmutants is not yet properly known, but it can be stated that in some cases they aggravate embrittlement and swelling.

The lack of a high-flux neutron source with a comparable spectrum to that of the fusion reactor necessitates simulation of irradiation damage with lower-energy neutrons or with ions (5,6). In irradiation in a fission reactor a correct ratio between helium production and dpa can be obtained, through adjusting the neutron spectrum, only with alloys containing nickel, because of the high thermal cross-section of the reaction $^{59}\mathrm{Ni}(n, \alpha)$.

Simulation with accelerated ions having an energy of some tens of MeV can be performed only on very thin samples, if a uniform damage state is required, as the penetration range is much less than a millimetre. Miniaturization of samples for mechanical testing is currently a florishing area of research (7,8), because construction of an intense neutron source (9), in other words a machine capable of producing a high flux of high-energy neutrons, would in any event provide researchers with a very small test volume, of the order of a cubic decimetre, incompatible with the dimensions of standard test specimens.

Though there are obvious difficulties in predicting the mechanical behaviour of complex structures from irradiation experiments that simulate their real working conditions, simulation is at present the only available means of studying basic phenomena and selecting structural materials. Only by constructing the intense neutron source and the experimental reactor will it be possible to verify the validity of extrapolation of results of simulation tests, and here again within the planned relatively modest dose limits.

Plasma/wall interaction

The energy associated with alpha particles is carried outside the plasma by a high energy ion and neutral atom flux and by electromagnetic radiation. This energy is intercepted by the first-wall components, resulting both in thermal fatigue connected with the cyclic nature of the reactor's functioning and in a phenomenon of erosion or sputtering of the material.

The atoms sputtered from the surface penetrate the plasma, where they become ionized. This erosion phenomenon is therefore doubly harmful: it constitutes a limiting factor of first-wall life, and at the same time, by increasing the impurities in the plasma, it moves it farther from ignition conditions.

Should operating conditions make for substantial sputtering of the structural material, the initial first-wall thickness must be increased to offset the losses with a sacrificial coating of such a nature as not to contaminate the plasma, that is, with a material of low atomic number or of negligible sputtering yield.

In present machines, in certain operating conditions, plasma instability phenomena occur, in which the plasma, by mechanisms as yet unknown, escapes from the sort of magnetic cage that confines it, and releases its stored-up energy. This involves hundreds of MJ which in a time in the millisecond range are discharged into the first-wall surface, causing a very high thermal shock. There is a rapid rise in the surface temperature, with possible local fusion and evaporation of the material (10). During resolidification there may be nucleation of shrinkage microcracks, which may propagate under the electromagnetic forces created by interruption of the plasma current and the thermal stresses due to normal operating cycles and prejudice the structural integrity of the components affected by the phenomenon.

Plasma disruptions, as they are called, are currently the subject of careful investigation in JET, both to discover their origin and temporal development and to try to prevent them or mitigate their effects. However, it seems inevitable that they will occur in NET. Present calculations assume a disruption frequency of one for every thousand normal cycles.

Protection from thermal shock caused by plasma disruption is provided in JET by a system of protective tiles of material with a low atomic number, fixed mechanically to the underlying structure. Similar solutions are being considered for NET, even though in view of the energy deposition values and the high number of operating cycles a solution of this kind does not seem altogether convincing. As an alternative the behaviour of protective coatings of low-sputtering refractory material is being studied (11).

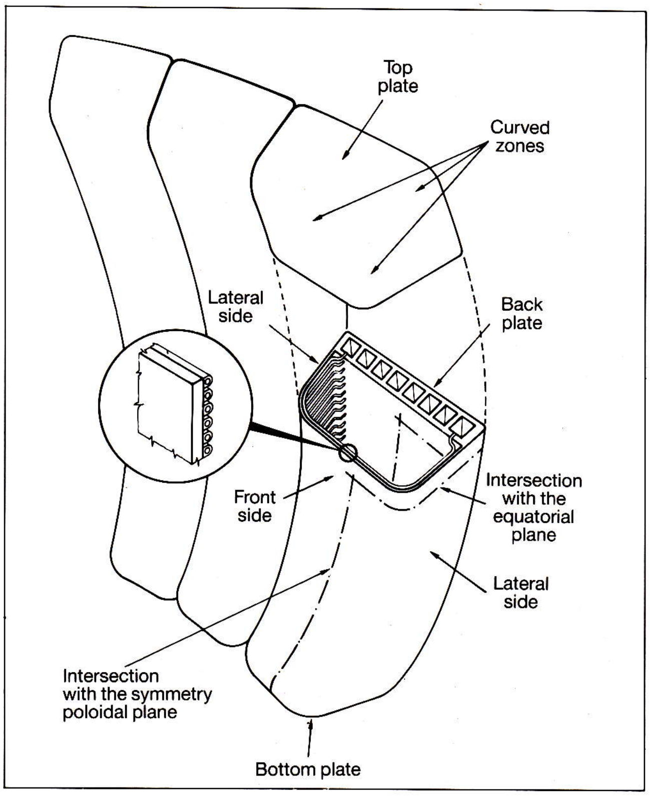

Fig. 2 - Schematic drawing of first wall and constructional detail of the part exposed to the plasma.

Selection of materials for first-wall components

Experimental reactor

Considering the foregoing, we can attempt to make a list, certainly not a comprehensive one, of requirements for the components concerned, which:

- must not contaminate the plasma with elements of high atomic number;
- must not be damaged or eroded through interaction with the plasma;
- must resist pulsed thermal loads, mechanical loads due to coolant pressure and structure weight, and electromagnetic loads due to volume forces that develop through interaction of the variable magnetic field with induced currents in the material;
- must not be subject to corrosive attack by the coolant or breeding material;
- must maintain adequate dimensional stability and structural integrity within the reactor's specified dose limits;
- must constitute an effective barrier to the permeation of tritium from the plasma chamber to the coolant;
- must limit the amount of tritium in the solute state in the structural material.

If it is added that the components must be timely designed, in the face of considerable margins of uncertainty as to the material's behaviour, must be fabricated in complex shapes, and must be tested in conditions that only partly reproduce actual working conditions, it becomes evident that the choice of structural material must be an alloy of which we already have solid experience in the nuclear field. That explains why the first candidate for NET's internal structures was an austenitic steel of the AISI 316 type.

Recently, however, under the weight of doubts as to the thermal fatigue resistance of austenitic steel, and with the intervening change of heart regarding the use of non-ferromagnetic materials, the way has been opened to the Cr-Mo martensitic or ferritic steels. In particular, the martensitic steel DIN 1.4914 is being considered as a possible alternative to austenitic steel (12). Both materials, whose principal properties are given in Table 2, have been extensively studied as part of the fast reactor development programme and particularly in regard to the former there is wide experience relating to its behaviour under irradiation. Both, too, are included in the nuclear design standards. Austenitic's weakness as compared with ferritic steels and vanadium alloys (see below) is its unfavourable combination of physical and mechanical properties for an application in which thermal stresses are prevalent and exceed the yield point. The high coefficient of expansion and low thermal conductivity mean that the

TABLE 2 - Physical, mechanical and neutron properties of some structural materials

	Austenitic steels	Ferritic steels	Vanadium alloys
Melting temperature, °C	1400	1420	1890
Maximum operating temperature, °C	450	550	650
Density, Mg/m^3	8.0	7.8	6.1
Coefficient of thermal expansion at 400°C, $10^{-6}/K$	18	12	10
Thermal conductivity at 400°C, W/mK	20	27	27
Electrical resistivity at 400°C, $\mu\Omega m$	1.01	0.91	0.67
Specific heat at 400°C, J/kg K	560	600	535
Neutron damage, $dpa/MWa/m^2$	11	13	11
He production, $ppm/MWa/m^2$	150	105	55
H production, $ppm/MWa/m^2$	570	540	240
Maximum heat flux, MW/m^2*	0.09	0.18	0.26

* The flux that does not induce fracture in a 10 mm plate in 10^6 thermal fatigue cycles

cyclic strain range is twice as high as in a ferritic-martensitic steel. Numerous analyses agree in identifying thermal fatigue, whether aggravated by plasma disruptions or not, as the limiting factor of the life of austenitic stainless steel first-wall structures (13-15).

The problem of present ferritic and martensitic steels is the ductile-brittle transition they exhibit at low temperature. By the effect of irradiation, even at relatively modest doses, the transition temperature rises by 100-200 H°C and the toughness upper shelf tends to diminish. For the experimental reactor, which being experimental will remain at ambient temperature for much of its life, this brittleness phenomenon may constitute a great limitation on the use of ferritic steels. Research into materials for NET's first-wall structures (16) is therefore directed at expanding the data base needed for design work and solving the problems connected with the fabrication and qualification testing of those components.

At the Joint Research Centre studies are in progress regarding the behaviour under ion and neutron irradiation (17) of various materials that have been proposed for NET's first wall and divertor. In addition, in collaboration with Ansaldo Ricerche SpA, the first-wall project shown in Fig. 2 is being developed, with the objective of testing the feasibility of such a component and its soundness under the combined action of thermal fatigue and plasma disruptions, to gain information that will help to develop design standards (18-20).

The choice appears broader in regard to materials for protection from the effects of plasma/wall interaction and materials for high-thermal-flux components such as the plates of the divertor. For protective materials the choice is open between graphite, beryllium, silicon carbide, boron nitride, silicon nitride and aluminium nitride, whereas for the divertor plates low-sputtering materials must be used, such as tungsten and molybdenum and their alloys. For the heat extraction structure the choice is necessarily limited to pure copper or a high-thermal-conductivity copper alloy. Steel/copper composite structures are also being considered for cases where the pressure of coolant fluid cannot be contained by copper (21).

The commercial reactor

A necessary condition for the development of a commercial reactor will be to find answers to problems of plasma/wall interaction, above all in regard to the occurrence of plasma disruptions and the quantity of material eroded. To be economic, the commercial reactor will need a high load factor and therefore must operate in stable or near-stable conditions, that is, with plasma ignition phases lasting many hours. Therefore, even though total fluence will be high, the lifetime

TABLE 3 - Maximum permissible concentration according to recycling and burial criteria (22)

Element	Recycling	Burial	Element	Recycling	Burial	Element	Recycling	Burial
1 H	NR	NR	25 Mn	NR	NR	62 Sm	10	0.2%
4 Be	NR	NR	26 Fe	NR	NR	63 Eu (0.2)	0.01	0.1%
5 B	NR	NR	27 Co	5	5%	64 Gd	1	10-50
6 C	NR	NR	28 Ni	0.1%	2%	65 Tb (0.5)	0.01	2
7 N	NR	0.1%	29 Cu	0.1%	0.5%	66 Dy	10-50	0.1-0.5%
8 O	NR	NR	30 Zn	50%	10%	67 Ho (0.01)	0.05	1
12 Mg	NR	NR	39 Y	NR	NR	68 Er	1-10	100
13 Al	100-500	0.5%	40 Zr	1-5%	10%	69 Tm	100	0.3%
14 Si	20%	NR	41 Nb	1	10	71 Lu	1	10%
15 P	NR	NR	42 Mo	50	500	72 Hf	0.1	0.1%
16 S	NR	20%	46 Pd	10-50	0.5%	73 Ta	50	NR
19 K	100	0.2%	47 Ag (0.5)	0.01	2	74 W	0.5%	5-10%
20 Ca	0.1-1%	1-5%	48 Cd	20	0.2%	75 Re	500	0.1%
22 Ti	5-10%	NR	50 Sn	10-50	1-5%	76 Os	1-5	50-100
23 V	NR	NR	55 Cs	100-500	NR	77 Ir (0.1)	0.1	10
24 Cr	NR	NR	56 Ba	10-50	50%	78 Pt	50	1%
						83 Bi	1	100

Values in ppm or wt percent (%); NR = no restriction.
Values in brackets indicate minimum impurity level thought to be obtainable with present production technologies.
Elements normally absent from structural materials and having a maximum permissible concentration exceeding 100 ppm are not listed.

number of cycles will be at least an order of magnitude lower than that predicted for NET. Problems of thermal fatigue and plasma interaction will consequently take second place, and those connected with irradiation damage, safety and environmental impact will become decisive. In short, the commercial success of fusion technology will be closely linked to the ability to develop materials capable of enduring high irradiation damage and minimizing the effect of neutron damage that has most environmental importance, the production of biologically dangerous radionuclides with a long half-life. The choice of the materials for the first-wall structure, which by itself contributes 50% of the radioactivity inventory though constituting less than 1% by weight of the nuclear block, determines which radionuclides will be produced and in what quantity. Calculations of neutron activation (22) show that by using elements within the percentages listed in Table 3 for the first wall it is possible to limit residual radioactivity 100 years after shutdown of the reactor to values that will allow first-wall materials to be recycled or buried without special precautions. Materials science and engineering are therefore required to solve a twofold problem:

1) to develop a structural material that will have the necessary combination of physical and mechanical properties for operating with the necessary reliability in an extremely hostile environment, using elements within the limits shown in Table 3;
2) to develop a process of material production and component fabrication that will guarantee the elimination of harmful elements down to ppm or even ppb level.

The first aspect of the problem is currently being tackled in the various countries concerned in developing this technology, starting from the knowledge acquired on alloys of equivalent composition, but it is only recently that limited attention has been directed to the second, which is not less difficult, for it requires the transfer of techniques of analysis, purification and processing of alloys, currently used only on a laboratory scale or for small-scale production, to the fabrication of major components.

I shall confine myself here to some remarks on the first part of the problem, leaving the second, though no less important, simply as stated.

It can be seen from Table 3, and particularly from the critical concentrations of Ni and Mo, that only a few of the many materials so far considered for the first wall can be defined, with suitably selected compositions, as materials of low induced radioactivity — specifically, austenitic steels and duplex steels based on the Fe-Mn-

Cr-V system, ferritic-martensitic steels based on the Fe-Cr-W-V system, and vanadium alloys of V-Ti and V-Cr-Ti type.
Even though the technology of ceramic materials is still very far from allowing them to be considered as structural materials for fusion, it is worth mentioning silicon carbide for the sake of completeness, particularly because according to a recent analysis (23) it minimizes the risks of accidental release of radioactivity during reactor operation.
Table 2 compares the physical, mechanical and neutron properties of the two steels selected for NET and those of a vanadium-chromium-titanium alloy.
The values in the table, which relate to neutronically "dirty" materials now available and not to those optimized for fusion, should be taken as targets to be attained with the corresponding "clean" alloys.

The difference in degree of development of these materials should be emphasized. "Clean" steels, whether austenitic or ferritic, differ appreciably in composition from their counterparts used today. Various compositions are currently being studied for the austenitic (4, 24-26), ferritic (27) and martensitic (28) matrices. The steels involved are obviously experimental, but it is possible to draw on the vast mass of existing data on the AISI 300 series and Cr-Mo steels. Development is therefore being guided and assisted by thorough experience of the general behaviour and properties under irradiation of the latter steels.
For vanadium the situation is completely different. A number of vanadium alloys, V-Ti, V-Cr, V-Cr-Ti, were studied in the 1960s in connection with the development of fast reactors (29). Impurities apart, these alloys already come within the selection criteria of Table 3. Specific data on them, including irradiation data, are available, but to a very limited extent.
An analysis of the long-term prospects of "clean" materials can be attempted, starting from current knowledge of certain aspects of the behaviour of the austenitics and ferritics under irradiation and of data of the vanadium alloys already developed. Irradiation experiments on austenitic steels have indicated a linear dependence of neutron swelling on the cumulative dose, beyond a critical dose (30). Composition and thermal and mechanical treatment have a strong influence on that dose without appreciably modifying the gradient of the curve, which for all steels of this class remains at about 1% volume swelling per dpa. The highest critical dose so far obtained is about 50 dpa, still a long way from the objective of more than 100 dpa needed to ensure the economics of the commercial reactor. The ferritic steels exhibit ten times lower swelling up to doses exceeding 100 dpa and a lower irradiation creep rate than in the austenitics at temperatures lower than 400°C (31).
Still to be solved is the problem of the increase with neutron damage of the ductile/brittle transition temperature, though in the commercial reactor it could be circumvented by keeping the structures in a safe temperature range.
Lastly, vanadium alloys seem to offer a prospect of greater advantages both in regard to irradiation resistance and on account of their more favourable mechanical properties, which would permit a higher operating temperature with evident advantages for reactor efficiency.
More detailed information can be found in a recent survey (32), which discusses possible advantages and limitations of vanadium alloys as structural materials for fusion. Advantages over steels are the physical, neutron and mechanical properties, irradiation resistance and compatibility with liquid metals. Possible limitations may be found in fabricability, cost, compatibility with coolants (water or helium) and hydrogen embrittlement.

Conclusions

Like every other advanced technology, fusion requires a major research effort in the area of materials. Research for the experimental reactor is directed towards optimization of existing materials, but for the commercial reactor completely new possibilities are emerging in the area of materials for the first wall and the blanket. The objective pursued is to prepare steels or vanadium alloys which will reduce the radioactivity induced by the neutron flux to minimum levels through control of the composition. It will thus be possible to exploit this inexhaustible energy source at extremely low environmental cost as compared with traditional nuclear energy.

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