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TOKAMAK REACTORS AND STRUCTURAL MATERIALS

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A summary is given of the status of the tokamak as a reactor concept and the relationship between first wall and blanket materials behavior and reactor design.

1. INTRODUCTION

The tokamak is the leading magnetic confinement approach to fusion power and it has been the most intensely examined of any concept in terms of reactor relevant issues. In this paper, we will summarize briefly the present status of tokamaks as a reactor concept, and the interrelationship between materials behavior and reactor design.

The tokamak is a toroidal plasma confinement device characterized by a major radius R, a plasma of radius a, a strong toroidal magnetic field, B_T, a substantial current carried by the toroidal plasma itself, I_p, and a poloidal field, B_p, produced by the plasma current. The physics performance of plasmas in tokamaks continues to improve and the Princeton Large Torus [1,2] with intense neutral beam heating ($\sim$2 MW injected) has produced plasmas with a central ion temperature in excess of 6 keV. Only $\sim$4.5 keV is required to achieve ignition in a D-T mixture when the dominant energy loss is bremsstrahlung. More importantly, the rate of collisions at the center of PLT is typical of that expected in a reactor, yet no excessively large energy loss was observed. The indications are that the dangerous trapped particle modes [3], which were thought to produce rapid energy transport in the low collision frequency range, apparently saturate at low levels.

Experiments on the high field tokamak, Alcator-A, have shown that stable plasma operation is possible when the plasma safety factor q is less than 3 [4]. q is defined as B_T/AB_p where A is the plasma aspect ratio defined as R/a. Low q operation is important because it can permit reactor plasma operation at high power density. The power density in a tokamak plasma varies as

$$P \propto \beta^2 B_T^4 \propto \frac{\beta_p^2\, B^4}{q^4 A^4}$$

where β is the plasma pressure divided by the total magnetic field pressure and β_p is the plasma beta measured with respect to the poloidal field associated with the plasma current. The motivation is thus to achieve not only low q operation but also high β in low aspect ratio machines. The aspect ratio can be effectively lowered by going to noncircular plasma shapes such as the "D" and the doublet. No experimental tests of β limits have yet been performed but theoretical predictions suggest 5-10% will be the limit on total β.

Important progress has also been made in producing clean tokamak plasmas and a start has been made on understanding plasma-wall interactions. The work of Taylor [5] has clarified the role of oxygen in plasma machines and demonstrated how oxygen can be removed by conversion to water in low temperature discharges. Titanium gettering is also regularly used to control light impurities and hydrogen recycle. High atomic number impurities coming from the walls and the limiter can be controlled by maintaining the plasma edge temperature at a low value (typically less than 10 eV) using programmed neutral gas injection. In addition several experiments incorporating different types of magnetic divertors have shown that such devices can reduce the influx of impurities [6,7]. The result of all this is that essentially all tokamaks today have an effective Z, defined as

$$Z_{eff} = \sum_j \frac{n_j Z_j^2}{n_e} ,$$

close to one. Here, n_j is the density of the ion species, Z_j is its atomic number, and n_e is the electron density. The sum extends over all ion species. A review of progress in this area has been given by Ginot [8].

Ultimately, the scaling of the energy confinement time in tokamaks will determine how reactor plasmas will burn. To this point, the variation of the plasma characteristic energy containment time, τ_E, goes approximately as na^2 (first found in Alcator-A) even in experiments where large amounts of external power are injected to heat the plasma. The temperature dependence of the scaling law remains uncertain although the recent PLT experiments suggest $n\tau_E$ may actually increase with T. No satisfactory theoretical model has yet been developed to explain this favorable empirical result.

Overall, progress in the physics of tokamaks continues to support their role as the leading magnetic fusion reactor candidate. Their reactor prospects have also changed in recent years, due in no small part to the influence of predictions regarding materials performance in a reactor environment. We will now describe recent changes in the concept of tokamaks as reactors, then proceed to discuss the issues relating to materials selection in fusion reactors, and finally outline trends and key issues, both for tokamaks as reactors and for materials performance.

2. RECENT TRENDS IN TOKAMAK REACTOR DESIGN

Since the early conceptual reactor designs, tokamaks as reactors have tended toward more compact designs of higher power density and higher neutron wall loading. The trend can be observed from the parameters given in Table 1 for several reactor designs developed in recent years. The trend towards greater compactness has been motivated primarily by the anticipation of potential economic improvements and by the desire to demonstrate that tokamaks of modest size, as well as large units, can be made into reactors. Cross section views of three recent designs are shown in Figs. 1,2,3.

Table 1

Evolution in Conceptual Tokamak Reactor Designs

Parameter	UWMAK-I [9] (1973)	UWMAK-III [10] (1976)	JÜLICH [11] (1977)	ORNL-DEMO [12] (1977)	HFCTR [13] (1979)	NUWMAK [14] (1978)
Major Radius (m)	13	8	6.9	6.2	6	5.2
Plasma Radius (m)	5 (b/a=1)*	2.5 (b/a=2)	1.8 (b/a=1.7)	1.5 (b/a=1.6)	1.2 (b/a=1.6)	1.1 (b/a=1.6)
Thermal Power (MW)	5000	5000	5000	2150	2470	2300
Electric Power (MW)	1450	2000	~2000	825	775	620
Structural Material	316 S.S.	TZM	Mo/S.S.	Modified 316 S.S.	TZM	Ti
Coolant	Li	He	He	He	FLIBE	H_2O
Breeding Material	Li	Li	Li	Li	Li	$Pb_{38}Li_{62}$
Neutron Wall Loading (MW/m2)	1.25	2	7.3	2.7	3.4	4

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* $\frac{b}{a}$ = plasma height to width ratio

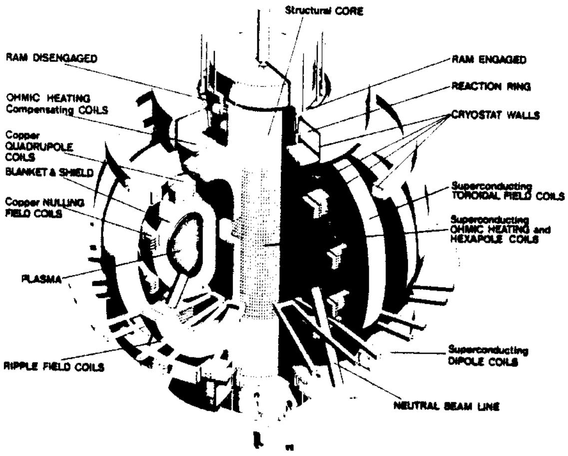


Fig. 1. High Field Compact Tokamak Reactor Design by MIT [13].

The high values of neutron wall loading, when coupled with the appreciation that limited materials lifetime will require periodic blanket replacement, has lead to designs aimed at improving access and maintainability. In the NUWMAK study (see Fig. 3), only eight superconducting toroidal field magnets are used (see Fig. 4). This leaves more than 5 meters between coils on the midplane at the outside for access. The ripple in the magnetic field is corrected by a set of normal water cooled copper trim coils, or

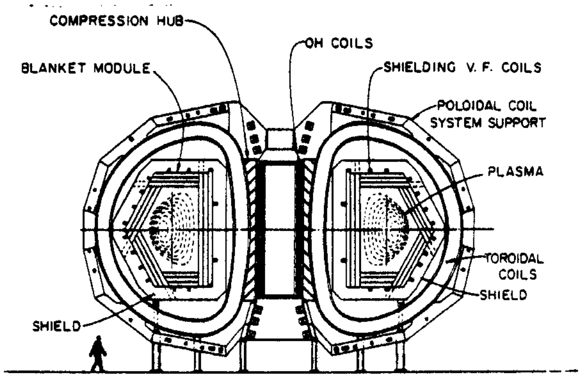


Fig. 2. ORNL Demonstration Reactor Design [12].

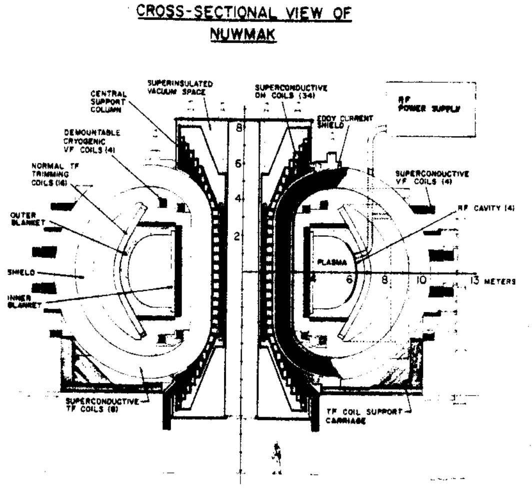


Fig. 3. The NUWMAK Tokamak Reactor Design [14].

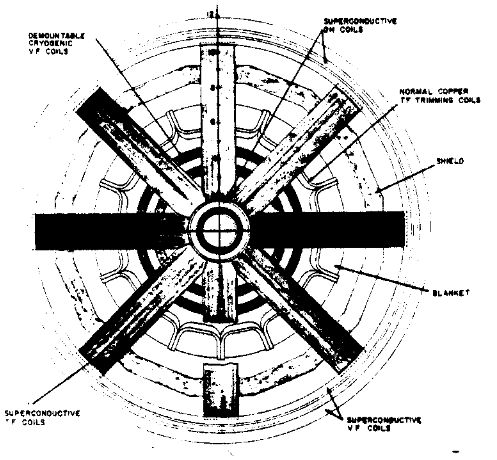


Fig. 4. Top View of NUWMAK Reactor. There are only 8 superconducting toroidal field coils and 16 copper trim coils.

saddle coils. These correction magnets do not encircle the blanket and are readily accessible from the outside. Access and modular blanket design are two elements that have received attention in essentially all reactor concepts.

Another trend is the development of blanket designs guided by experimental materials data. Two examples are the choices for the structural material and operating temperature in the ORNL Demonstration Tokamak Study [12] and the Wisconsin Tokamak Engineering Test Reactor (TETR) Study [15]. Experimental data developed by Bloom et al., [16] for 316 stainless steel show that at high temperature (>500°C) there is a sharp loss of ductility due to helium embrittlement. However at lower temperatures (less than 450°C), a finite residual ductility remains even at high fluence and swelling rates are modest.

Using a theoretical model, Wolfer and Conn [17] showed that swelling should drop to very low levels when the temperature is reduced further, say to 300°C, but that the residual ductility remaining (~.5%) should provide sufficient fracture toughness for the material to resist crack propagation. The first wall temperature in the ORNL study was chosen at 400°C and in the TETR study at 300°C. Recent measurements by Wiffen [18] on 316 SS irradiated at 55°C confirm that a residual uniform elongation of ~0.5% remains, that irradiation has little effect on total elongation or strength properties, and that swelling is unmeasurably small.

In all reactors, the lifetime prediction for the blanket structure is highly dependent upon design. The trend is towards detailed analysis based on structural analysis and materials performance in a particular design environment [19]. We will cover this in somewhat more detail in the next section. A major issue, however, that has not received significant attention is first wall reliability and redundancy. In a tokamak or other magnetic confinement device, the vacuum integrity can be compromised by a single leaker in the first wall. This may be contrasted to fission reactors where the development of leaking fuel rods in limited numbers does not severely affect operation. In tokamaks, where remote access and maintenance will be complicated, there is a true economic premium to preventing essentially all first wall failures. Thus, along with improved materials performance, there is a need to develop highly reliable first wall designs that can operate with a low failure probability for the estimated life of the component.

Whether a tokamak reactor will require a divertor for impurity control, pumping, and long burn times is an area where no clear design trend exists. It is recognized by all that impurity control is essential and the use of low Z liners and limiters in early reactor studies is now being implemented in tokamak experiments. In the PLT device, the original tungsten limiter has been replaced with a water cooled graphite limiter and a marked improvement in experimental parameters was achieved. The development of low Z coatings for limiters and liners in experiments is a clear imperative. On the other hand, the approach to employ in a reactor is far from clear.

Recent designs, such as the HFCTR [12] and NUWMAK [13], employ gas injection on the outside to simultaneously fuel the plasma and control the density and temperature profiles to prevent impurity buildup. It is found however that very high surface heat loads (~500-1000 W/cm^2) may still occur at the limiter and that the power output from the plasma can oscillate 10 to 20%. Most early tokamak studies included a poloidal magnetic divertor for impurity control but all studies show that this approach significantly complicates the design, construction, and maintenance of the device. Recent work by

Yang and others at Westinghouse [20] indicates that a bundle type divertor may be feasible although it produces a substantial magnetic field ripple in the plasma that is detrimental to confinement. Finally, the heat load at the divertor collector plate can be very high (>1 kW/cm^2) and there are major questions related to sputtering and arcing which will impact the lifetime of the collectors. In poloidal divertors, access to and maintenance of the collectors is a major issue.

All tokamak reactor designs developed so far are based on the assumption that the plasma burn is limited. Typical burn times range from 60 seconds in near term designs to 200-2000 seconds in conceptual power reactors. In either case, the down time between burn pulses will cause temperature and stress cycling to occur in the blanket. Thus, fatigue is a major issue. Recently, several designs have chosen to use boiling water cooling in an attempt to minimize temperature cycling. Sze et al., [21] have proposed using a Pb-Li eutectic with a melting point of 464°C which would alter its liquid-solid fraction during the down time in order to maintain an essentially constant heat flux to the blanket cooling tubes. The surface heat flux, however, is not simulated during the down time so that the temperature fluctuation on a first wall cooling tube can be 100°C.

Finally, many near term tokamak reactor designs have been developed and two major new studies are just beginning. These are for the U.S. Engineering Test Facility (ETF) and the International Tokamak Reactor (INTOR). Earlier studies of experimental power reactors (EPR's), ignition test reactors (ITR's), and next step devices (TNS) summarized in the conference report by Conn et al.,[22] appear to show that there are no identifiable bulk materials problems which would jeopardize the performance of these devices. However, as discussed earlier, the dilemma over gas puffing or divertors for impurity control makes the development of low Z materials or coatings for limiters and/or the first wall an important near term problem.

3. CRITERIA FOR SELECTING FIRST WALL MATERIALS

In an earlier paper, we discussed criteria for selecting first wall materials in fusion reactor design [23]. A priority list of criteria is given in Table 2 and, as might be expected, no one material is clearly favored and the final choice will depend upon the objectives of a reactor design. Radiation damage is the most important criteria because is has the greatest influence on material performance and lifetime. It therefore affects the design in terms of reliability and maintainability. On the other hand, materials in near term reactors will have low irradiation exposures and the criteria for material selection will be reordered. A priority list of criteria for near term experimental reactors is given in Table 3.

Materials actually selected in near term experimental tokamak reactor designs are summarized in Table 4 together with the primary reason the material is selected. One can see that, overall, the near term reactor requirement to select a material for which there is an industrial capability and an extensive data base dominates all other factors. By contrast, the materials selected in conceptual reactor designs cover a wider range and reflect a balance between different design objectives. An extensive list is given in Table 5.

Without developing a complete discussion of every item on Table 2 we can make some specific comments. On radiation damage, the only well characterized material is stainless steel. Data exist for other materials, such as Al, C, Mo, and V, but this is typically low fluence data without helium gas production. Titanium and vanadium alloys do not show signs of swelling in low fluence neutron irradiation tests or in heavy ion simulation, but high fluence data are not available nor are data for samples with high helium content.

The thermal properties of materials can be effectively compared in terms of the thermal stress parameter, M, defined as

$$M = \frac{2\sigma_y k(1-\nu)}{\alpha E}$$

where σ_y is the yield strength, k is the thermal conductivity, ν is Poisson's ratio, α is the coefficient of thermal expansion, and E is Young's modulus. Large values of M are most effective in reducing thermal stress. A graph of M versus temperature for several materials is shown in Fig. 5 and explains the priority ordering in Table 2.

Compatibility is a key issue in selecting first wall materials. Oxygen pickup and embrittlement in V and Nb alloys effectively rules out helium as a coolant. It is not feasible in a practical way to maintain the oxygen content in the helium at the part per billion level. Excessive corrosion eliminates the use of aluminum alloys with liquid metal coolants and limits the maximum operating temperature of steels (and nickel based alloys) to about 500°C. The solubility and diffusivity of tritium is low in Mo, Al and steel but high in V and Nb at their anticipated operating temperatures. The need to double-line high temperature piping to prevent excessive tritium leakage has been found to present a severe economic penalty [10] which could rule out these alloys even if they were acceptable on other grounds.

A comparison of induced radioactivity as a function of time after reactor shutdown is given in Fig. 6. V-20Ti is most favored on this basis but other choices, such as aluminum [31] and titanium alloys [33] and graphite, are also quite good. This points to an important general feature of fusion, namely that long lived radioactivity is not inherent to the process and can be controlled by appropriate selection of structural materials.

4. SUMMARY

The trend in tokamak reactor design has been towards units which are more compact, have high power density, and have a neutron wall loading in the range 2-4 MW/m^2. The impact of materials performance and limited lifetime has led to designs which emphasize access and maintenance and to blanket concepts that are aimed at minimizing cyclic stress loadings while operating at an optimum temperature from the viewpoint of radiation damage. The complexity associated with magnetic divertor design has led to intensive study of alternative means of fueling and impurity control such as periodic gas puffing. However, no clearly workable approach has yet been established so that the continued development of low Z materials and coatings is essential. So too is our improved understanding of the plasma-wall interaction process. A high neutron wall loading means that there will be a high surface heat loading on the limiter or divertor collector plate and on the first wall. As such, processes like sputtering and arcing may severely limit the lifetime of these components and much further development is needed.

Most major alloys have now been studied in the context of a tokamak reactor design and the primary choice for the structure continues to be either a steel or a nickel based alloy because of the large existing data base and the extensive industrial capability. Vanadium and titanium alloys appear to be the logical backup

Table 2

Criteria for Selecting First Wall Materials* in Fusion Reactors in General Priority Order

Criteria	Favored Materials	Less Favored
1. Radiation damage and lifetime		
a. Swelling (dim. stability)	Ti, V, Mo, SS	Nb, Al, C
b. Embrittlement	C, Nb, V, Ti, SS	Mo, Al
c. Surface properties	V, Ti, Al, C	SS, Nb, Mo
2. Compatibility with coolants and tritium		
a. Lithium	Ti, V, Nb, Mo, SS	(Al, C)**
b. Helium	SS, Ti, Mo, Al, C	(Nb, V)**
c. Water	SS, Al, Ti	(C)**
d. Tritium	Mo, Al, SS	Ti, V, Nb, C
3. Mechanical and thermal properties (irradiated)		
a. Yield strength	Mo, Nb, V, Ti, SS	Al, C
b. Fracture toughness	SS, Ti, Al	V, Nb, Mo, C
c. Creep strength	Mo, V, Ti, SS	C, Al, Nb
d. Thermal stress parameter $M \equiv \frac{2\sigma_y k (1-\nu)}{\alpha E}$	Mo, Al, Nb, V	Ti, SS, C
4. Fabricability and joining	SS, Al, Ti	Nb, V, Mo, C
5. Industrial capability and data base	SS, Al, Ti, C	Mo, Nb, V
6. Cost	C, Al, SS, Ti	Mo, Nb, V
7. Long lived induced radioactivity	V, C, Ti, Al	SS, Nb, Mo
8. Resource availability (USA)	C, Ti, Mo, Al, SS	Nb, V

* Alloys. Ti-6Al-4V, V-20Ti, TZM, Nb-1Zr, 316 SS, Al-6061. This is an illustrative list.

** Materials in parenthesis are unacceptable with stated coolant.

materials. Vanadium alloys have the best thermomechanical properties and low induced radioactivity levels. They may also prove to be quite resistant to radiation damage although no data are available with high helium content. A major drawback at this time is the absence of an industrial capability and standards. Titanium alloys have good fatigue properties, are compatible with all potential coolants and can have low levels of induced radioactivity. There is also a large titanium industry associated with aircraft applications. The drawbacks are that such alloys would have a relatively narrow operating range because below about 250°C, there will be extensive tritium pickup while above 450°C, the alloys undergo an unfavorable phase transition (from the α to β phase).

Table 3

Criteria for selecting wall materials in near term experimental fusion reactors

1. Industrial capability and existing data base
2. Compatibility with coolants and tritium
3. Fabricability and joining
4. Mechanical and thermal properties
5. Induced radioactivity
6. Cost
7. Radiation damage

Finally, a redundant, highly reliable first wall design must be developed both for tokamaks and other magnetic fusion reactors. The required high vacuum integrity makes it imperative that the probability of a first wall cooling tube failure be very low over the anticipated operating lifetime. As yet, no completely satisfying design which would meet this requirement has been developed.

In spite of such outstanding issues, the concept for the tokamak as a reactor has altered and improved considerably in recent years. No fundamental technical issue has been uncovered, and with continued improvement in the physics and materials data base, the outlook for developing viable tokamak reactors is good.

Table 4

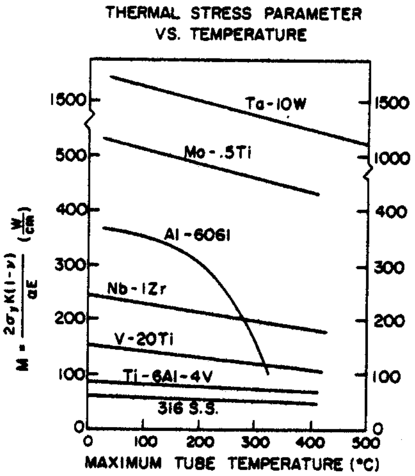
First Wall Material Selection in Near Term Fusion Reactor Designs

Study	Machine Objective	Material Selected	Primary Reason for Selection
TNS/ORNL-W (24)	Tokamak to follow TFTR	316 SS	Industrial capability plus data base
ITR/GA-ANL (25)	Tokamak Ignition Test Reactor	Inconel 625 + Be Coating	Efficiency with He cooling
MTF/JAERI (26)	Follow JT-60	Inconel 625	Not given
TETR/UW (15)	Tokamak Engineering Test Reactor	316 SS	Industrial capability, data base, adequate life
EPR/USA (27)	Experimental Power Reactor	316 SS	Industrial capability plus data base
EPR/JAERI (28)	Experimental Power Reactor	TZM+low Z coating	High temperature high efficiency operation
DEMO/ORNL (12)	Tokamak Demonstration Power Reactor	316 SS	Industrial capability, data base, adequate life

Table 5

First Wall Material Selections in Conceptual Tokamak Fusion Reactor Designs

Study	Material Selected	Primary Reason for Material Selection
UWMAK-I, II (9)	316 SS	Existing technology
ORNL (29)	Nb-1Zr	High temperature, high thermal efficiency
PRD (30)	PE-16	Low swelling
UWMAK-III (10)	TZM	High temperature, high thermal efficiency
BNL-tokamaks (31)	Al alloys	Industrial capability, low radioactivity
GA-doublets (22)	Graphite, SiC	Industrial capability, low radioactivity
Jülich-tokamaks (11)	316 SS + Mo	High temperature, high thermal efficiency
NUWMAK (14)	Ti-6Al-4V	Industrial capability, fatigue, properties, long life, low activity
ANL-parametrics (32)	V-20Ti	Long life, low activity, high temperature



(*M FOR Cu AT 20°C 727W/cm)

Figure 5

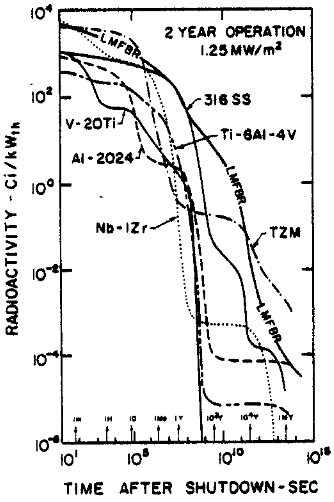


Fig. 6. Radioactivity in CTR Blankets After Shutdown Following Two Years of Operation

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