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ABSTRACT

The uniqueness of radiation damage associated with 14 MeV neutrons is discussed in relation to total displacements per atom (dpa), dpa rate, gas production rate, gas to dpa ratio, and solid transmutation products. Comparisons are made with both light water and fast reactors to illustrate that it will be very difficult to use the latter facilities to provide information about high power fusion reactors. The one exception to this statement pertains to 316 SS in thermal reactors where the proper helium gas generation rate is achieved. Examination of the displacement and transmutation damage with respect to the dimensional, mechanical and physical properties of metals reveals that there is very little, if any pertinent experimental data available. Providing this data will require a massive and time consuming test program that could spread over a decade or more. Considering the shear number of radiation damage problems and their magnitude leads one to believe that their solution will be a major barrier to the commercialization of fusion power, second only to those problems associated with plasma physics.

INTRODUCTION

The production of electricity by a controlled thermonuclear reactor can be one of the most important scientific achievements in the history of mankind. However, one must also recognize that such an achievement will require the successful solution of some of the most complex problems ever encountered by the scientific community. The production and confinement of a DT plasma will be difficult, time consuming, and at times, frustrating. Once that primary barrier is overcome, there will be several other obstacles that must be surmounted before the goal of economic fusion power can be achieved. These include the successful production, handling, and containment of tens to hundreds of kgs of tritium in a fusion plant, the assurance of structural integrity over relatively long periods of time in the face of an extremely harsh irradiation environment, and the engineering design of systems which are compatible with the resource, environmental and financial limitations that are facing every country in the world today. The object of this paper is to illustrate why it is felt that, next to the solution of the plasma physics problems, the effects of radiation damage to reactor structural components represent the second most serious obstacle to fusion power.

Such an exposure of the many materials problems is a colossal undertaking to say the least and we hope that it is done in a positive sense in this paper. The main purpose is to insure that scientists of all types, and materials scientists in particular, broaden their perspective to consider not only those problems with which they are individually acquainted with, but also those problems which so often stand between the scientific feasibility of a particular concept and the engineering feasibility of that concept.

The format of this particular paper is as follows. The anticipated irradiation environments of several types of fusion plants are first reviewed including the types and functions of various CTR materials. Next the displacement damage and transmutation characteristics are discussed, both as a function of position, and time in typical fusion systems. This is followed by a brief description of the general types of neutron damage anticipated in fusion reactors and some observations on state of the art of experimental data. Finally, the effect of these property changes on the effective lifetime of reactor components is discussed in terms of cost, resources, and long term radioactivity problems.

A final point to note is that this work will concentrate on bulk radiation damage by neutrons and will not be concerned with the surface damage produced by neutrons, photons, or particles leaking fron the plasma. This has been amply reviewed in previous conferences.[1-3] Such an omission should not be construed as implying surface effects are unimportant, but rather it is a result of the limited space alloted a review of this type.

OPERATING ENVIRONMENT FOR VARIOUS FUSION REACTORS

Materials

In contrast to fission reactors where there are perhaps 4 or 5 different classes of solid materials to worry about (fuel, cladding and core restraint, reflectors, control rods, and pressure vessels) there may be as many as 10 in fusion reactors. These general classes are listed below:

- Low Z liners
- Electrical insulators
- Structure
- * Solid tritium breeder material
- * Fissile breeder material
- * Neutron multipliers
- Reflectors
- Shielding material
- * Magnets
- * Optical systems

The functions of these materials have been reviewed before[4-6] and we will only briefly summarize the results here.

Tokamaks may require low atomic weight liners for plasma physics reasons (mainly to insure that excessive power is not leaked from the plasma by radiation from impurity atoms).[7-8] Such materials are placed in the vacuum region between the plasma and the first solid wall and therefore will be subjected to the most extreme temperature, charged particle, photon and neutron environments in the reactor. It is important that they last at least as long as the first structural walls in order to allow some chance for economical commercial operation.

Electrical insulators will be required in all magnetically confined systems in one form or another and in inertially confined systems (i.e. E beams). Both mirrors and tokamaks will require fueling systems (beams or pellets) which will probably rely on electrostatic acceleration. It will be difficult to shield such systems from the direct bombardment of neutrons and the associated damage to dielectric properties. Auxiliary

*only required in some systems

heating in Tokamaks may utilize RF sources which could contain dielectrics to reduce the size of the wave guides.[9] Unfortunately, such wave guides must "see" the plasma and therefore be subjected to all the radiation emanating from the plasma. Theta pinch reactors will require electrical insulators which can maintain dielectric strengths of up to 100 kV/cm while being pulsed some 3 to 10 million times per year.[10] This insulator must function at temperatures approaching 1000°C while being bombarded with copious amounts of atomic hydrogen and neutron fluences of up to 10^{22} n/cm^2/yr. Finally, the electrodes of E beam reactors will be subjected to very high fluxes and the associated degradation of properties has not been completely appreciated at this time.

The needs for structural vessels which provide vacuum tightness and are pulsed anywhere from 10 to 10^8 times per year are fairly well established and extremely demanding. Reflectors are required for efficient neutron utilization and protection of components outside the reactor. Shields are absolutely essential to prevent excessive radiation levels from occuring outside the reactor and to prevent damage to components not directly involved in the extraction of energy (i.e. magnets, lasers, fueling devices, etc.).

Breeding is, of course, absolutely essential for all the D-T systems. If liquid lithium is not used, then solid lithium containing compounds as Li_2O, $LiAlO_2$ or $LiSiO_2$ must be utilized.[11-12] We shall see later that these compounds have many of the same problems now facing us for fission reactor fuels with a few added features which could be quite difficult to overcome. For example, a very large fraction of the total energy is produced in these materials (normally ceramics) which promotes high temperatures and severe temperature gradients. In order to avoid large tritium inventories, the tritium must be constantly removed from the breeder. If radiation damage and high temperatures interfere with the diffusivity and/or the diffusion path of the tritium, very high tritium inventories could then occur.

The use of solid breeding compounds will almost invariably require the use of neutron multipliers such as beryllium. Ignoring the high cost per kg of Be and the lack of extensive Be reserves in the world for the moment,[13] one finds that severe dimensional problems could occur at high temperature due to high helium gas generation rates. It has even been proposed to surround the plasma with a blanket containing fissionable and/or fertile material.[14] Presently it seems that the later is more attractive and this would mean that the associated dimensional problems of U and Th compounds need to be considered along with radioactive fission products and associated safety questions.

The critical properties of superconducting magnets for tokamaks and mirrors, and conventional magnets for theta pinches must be maintained. In the first case, the critical currents, temperatures and fields of superconducting filaments must not be significantly reduced over long periods of time by bombardment with neutrons. The cryogenic stabilizers must retain a low resistivity value to insure safe operation in the event of a quench in the superconductor. The compression coils of a theta pinch reactor will be subjected to high neutron fluxes and operate well above room temperature. Significant transmutation reactions and displacement rates will result in changes in resistivity over long periods of time. Finally, one needs to be concerned about non current carrying components of magnets such as electrical insulators or thermal insulators. Failure of any of these components could require costly repairs and unacceptable down times.

The optical systems for laser reactors (such as mirrors and windows) must maintain extreme dimensional stability (to within a quarter of the wavelength or ~3000 Å) over long periods of time in a commercial system. Very little is presently known about the effects of neutron damage on the surface roughness and the subsequent effects on the efficiency of pellet compression or, the rate at which implosions can take place. This area is almost completely lacking in prior information and it is difficult to even estimate how serious of a problem may be encountered. In the worst case, the ultimate viability of a laser reactor could critically hinge on the successful solution of such problems.

An attempt to summarize the preceding discussion has been made in Table 1 where the potential materials, their functions, operating temperatures, neutron fluxes, and critical properties are listed. A detailed

Table 1

Materials for Fusion Reactors

Function	Typical Examples	T_{op} °C	ϕt s^{-1} $(MW/m^2)^{-1}$ 14.1 MeV	Total	Special Comments
		GENERAL			
First Wall and Blanket Structural Components	Austenitic Steels (AISI 304,316,347,etc.)	400-650	4×10^{13}	2×10^{14}	
	Nickel Based Alloys (PE16,Inconel,Incoloy,etc.)	500-700			
	Refractory Metals (V,Nb,Mo or alloys)	800-1000			Low Li Corrosion Resistance
	Aluminum Alloys	<300			
	Other (carbon, SiC)	~1000			Low Tensile Strength
Neutron Multiplier	Be, BeO, Be_2C	400-600 400-1000	$\sim 1 \times 10^{13}$	1×10^{14}	High He Gas Production
Breeding	Li LiAl $LiAlO_2$, Li_2O	300-1000 300-600 600-1500	$\sim 1 \times 10^{13}$	$\sim 1 \times 10^{14}$	High Gas Production
Reflection (Moderator)	Graphite (Steel)	400-1000	4×10^{12}	$\sim 2 \times 10^{13}$	High He Gas Prod in C
Radiation Shielding	B,B_4C.Pb,Steel	100-300	10^{11}	10^{13}	Thermalized Spectrum
		SPECIAL			
Electrical Insulation	Al_2O_3,MgO	500-800	4×10^{13}	2×10^{14}	~100 kv/cm pulsed operation
Optics for Laser System	Phenolics	-270	10^6	10^8	
Windows	Ge,NaCl,KCl,etc.	~100-200	up to 4×10^{13}	up to 2×10^{14}	Pulsed neutron fluxes and temp. loads
Mirrors	GaAs,CdSe,Cu,TiO_2 ZrO_2	~100	variable	variable	Extreme Dimensional Stability Req. (<3000 Å)
Thermal Insulation	Mylar	~240-270	$\sim 10^6$	$\sim 10^8$	High susceptibility to gamma irradiation
Superconducting Stabilizing Materials	Cu, Al	-269	$\sim 10^6$	$\sim 10^8$	Periodic annealing to R.T. can remove substantial damage
Superconducting Magnet Filaments	NbTi,Nb_3Sn	-269	$\sim 10^6$	$\sim 10^8$	"
Magnet Support Structure	Austenitic Steel, Al Alloys	-200 to +30	$\sim 10^6$	$\sim 10^8$	High Stresses (~2/3 σ_y)
Energy Multiplication	UO_2,PuO_2	800-1500	$\sim 10^{13}$	$\sim 10^{14}$	Temp. Gradients
Fissile Fuel Breeding	U	<500	10^{13}	$\sim 10^{14}$	Gas Swelling

discussion of these numbers is not warranted here because the quantitative numbers are somewhat design dependent. However, the reader will note the wide range of conditions and materials involved in fusion systems and can draw his own conclusions about the extent of the research program to establish engineering feasibility of CTR reactors.

Burn Cycle and Neutron Flux Effects

One of the most frustrating aspects of this type of analysis is that there are several potential (at least 5) avenues to fusion reactors and they all represent drastically different burn cycles. We will try to put all of these cycles in perspective with respect to the following quantities (see Table 2).

- time over which neutrons are produced
- time in which damage is done in materials
- time between burns

The information in Table 2 shows that the neutrons can be produced in burns which last from 10^{-9} to 10^{6} sec separated by times of 0.01 to 10^{5} sec. For all systems in which the burn time exceeds the neutron slowing down time (approximately a microsecond) the damage rate is constant over the burn time. However, in E beam or laser systems, the neutrons are produced in times much shorter than the slowing down time and consequently the damage occurs at a relatively long time after the initial burst of neutrons.

In principle, the mirror system could run in a steady state so that precise assessment of burn dynamics is not meaningful. However, it is unlikely that any system as complex as a fusion reactor could run continuously for more than a month without a mechanical failure which would require a shutdown of the reactor. Therefore, we have somewhat arbitrarily chosen 3×10^{6} seconds as a typical operating time.

The situation for tokamaks is somewhat unclear at the present time depending on the rate of buildup of impurities in the plasma, or the amount of flux swing that can be reasonably uncorporated into the transformer coils. It is quite possible that if impurity confinement times are significantly longer than fuel atom confinement times, the D-T burn

Table 2

Potential Burn Cycles for Various Fusion Reactor Concepts

Reactor Concept	Anticipated Neutron Pulse Length-sec	Time of Damage per Pulse-sec	Time Between Burn-Seconds	Number of Cycles/year 80% P.F.	Instantaneous 14 MeV Neutron Flux at an Ave. 1 MW/m^2 wall load ing over burn cycle(b
Tokamak	100–5000	100–5000	10-500	5000 to $2x10^5$	~5×10^{13}
Mirror	~3×10^6(a)	3×10^6	~10^5	10	4.5×10^{13}
Theta Pinch and Solonoids	0.3	0.3	3-10	~10^6	~4×10^{14}
Laser	10^{-9}	10^{-6}	0.01-1	10^7-10^9	~4×10^{17} to 4×10^{19}
E-beam	10^{-9}	10^{-6}	0.01-1	10^7-10^9	~4×10^{17} to 4×10^{19}
LWR-Fission Reactor	3×10^6(a)	3×10^6	~10^5	~10	2×10^{14}(c)
LMFBR-Fission Reactor	3×10^6(a)	3×10^6	~10^5	~10	~2×10^{15} (c)

(a) Limited by mechanical failures rather than physics considerations.

(b) Units of $n/cm^2/sec$, back scattered neutrons would increase the numbers by factors of approximately 5.

(c) Max. fluxes core center, E > 0.1 MeV.

cycle could be limited to as little as 100 seconds in a reactor. On the other hand, if the impurities diffuse out of the plasma at a sufficiently rapid rate, then economic limitations of incorporating flux swings of more than 500 V-sec may limit the length of the burn to a few thousand seconds before the magnets would need to be reset.

Theta pinch and solonoid reactors limit their burn times to a few hundred milliseconds due to a complex trade off between size of the plasma column, reasonable magnetic fields and rates of field buildup and assumptions on burn dynamics. It is unlikely that the burn times would be greater than one second and values of less than 10 milliseconds may be uneconomical in a magnetically confined system.

If one assumes that nominally, a time averaged 1 MW/m^2 wall loading is required for economical reactor operation, then one can obtain a rough approximation of the instantaneous 14 MeV neutron flux (in $n/cm^2/sec$) to the first wall. This ranges from ~4.5×10^{13} $n/cm^2/sec$ for mirrors and tokamaks to ~4×10^{14} for theta pinch and solonoid reactors, to as high as 4×10^{17} to 4×10^{19} for laser and E beam reactors. Of course, if back scattered neutrons are included, these values would have to be increased by factors of ~5 to get total neutron fluxes. We have included typical values for fission reactors in Table 2, which include all the fast ($E > 0.1$ MeV) neutrons. Even if the tokamak and mirror numbers were adjusted to include back scattered neutrons, we would find that the total neutron flux is considerably lower than in a liquid metal fast reactor. However, we shall see later that spectrum effects alters this picture in ways which are material dependent.

To summarize this section, we cannot state with any degree of certainty what the burn cycle and neutron flux conditions will be for the ultimate fusion system. There may be as much as a factor of 10^6 difference in damage rates not to mention the effect of annealing time between pulses on the final state of the damage. The best one can do now is to acknowledge the wide range of possible operating parameters and adjust research programs accordingly.

Spectrum Effects

The increased energy of the D-T neutron (14.1 MeV) over those typical of a fission spectrum makes the quotation of simple neutron fluxes and fluences of somewhat questionable value for fusion. Not only are there many more potential nuclear reactions to contend with (e.g. (n,n'p), (n,n'α), (n,2n)) but the primary knock on atom (PKA) energy is considerably higher. An appreciation of the spectral differences can be gained from Figure 1 where the neutron spectra from a fission reactor,[15] a typical fusion reactor,[16] a D-T neutron source[17] and a D-Li stripping source[18] are given. These numbers are plotted on an absolute scale so as to reflect the flux level as well as the energy spread of neutrons in these systems. The fusion spectrum has the traditional peak at 14 MeV followed by a down-scattered spectrum that peaks over several hundred keV. This is contrasted to the fission spectrum where the neutrons are emitted with a mean energy of ~1 MeV. Current D-T neutron sources are unable to provide sufficient backscattered neutrons to cause a significant deviation from the monoenergetic source while stripping sources such as D-Be or D-Li provide a broad range of energies which depend on the incident deuterium energy. For a 33 MeV deuterium on Be the neutron energy varies from a maximum of ~33 MeV to below 1 MeV with a maximum in flux at ~18 MeV.

The importance of such spectral effects on a few selected nuclear reactions is given in Table 3 where the spectrum averaged cross section for the helium gas reactions in metals are listed for a fusion reactor and a light water fission reactor. This table reveals that the (n,α) cross section for the metals examined here ranges from 100 to 1000 times higher in fusion reactors versus fission systems. (This is reversed for Ni containing alloys for reasons explained elsewhere.[20,21]) The ratio is even higher for the (n,2n) reaction in all metals. Such large differences are partially compensated for by the order of magnitude higher flux in fast fission reactors, but it is obvious that the magnitude of gas generation is still much higher in fusion reactors. This is also true for many other transmutations as we shall see later.

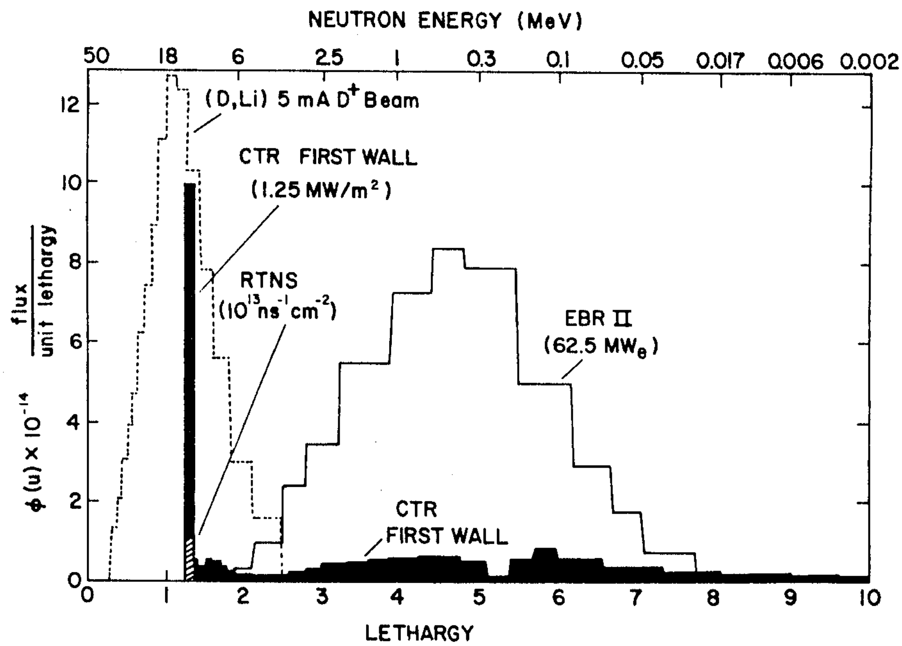


Fig. 1 - Typical Neutron Spectra for Various Nuclear Facilities

Table 3

Effect of Neutron Spectrum on Helium Production Cross Section

	Spectral Averaged Cross Section - milli barns	
Element	LWR[(a)]	CTR[(b)]
Mo	0.046	4.53
Nb	0.0255	2.37
V	0.06	5.24
316SS	~60[(c)]	20.36
Al	0.28	32.46

(a) HFIR (High Flux Isotope Reactor) core center[(19)]

(b) UWMAK-I[(16)] First Wall

(c) Due to thermal (n,α) reaction in Ni-59[(20)], value here is valid after one year of exposure.

The higher neutron energy also produces a considerably different PKA spectrum as shown in Figure 2. We have used the defect production code of Gabriel et al.[22] and plotted the PKA energy of Cu atoms in (1) a light water fission spectrum, (2) a typical CTR first wall spectrum and (3) a mono-energetic 14 MeV neutron flux. The first point to note is the large number of low energy events even in the higher energy neutron case. The second point is the maximum PKA energy is ~500 keV for the fission neutrons and ~2 meV for the fusion neutrons. The effect of such high energy knock on atoms on physical processes in metals is not clear at present but it is conceivable that it could mean increased resolutioning of fine precipitates, the generation of multiple defect clusters in close proximity to each other which might be very effective dislocation barriers or in increased overlapping of displacement spikes. This question is of course of fundamental importance in assessing the validity of any simulation scheme.

In summary, it is safe to say that we do not know precisely what effect the higher neutron energy of a D-T reaction will have on the physical and mechanical properties of metals at high fluences and at high temperatures. The increased transmutation rates and the higher PKA energies are not easily incorporated into present radiation damage theories and it would not be surprising if future experimentation produces a few "surprises" in materials behavior like those of fuel pellet sintering and voids discovered in fission reactors.

Spatial Effects of Neutron Fluxes

At first glance one might think that the neutron flux and energy spectra vary only with distance into the blanket and shield measured perpendicular to the plasma. In fact, this is probably true for laser and mirror reactors which are generally spherical in geometry. It may also be true for theta pinch reactors which are either cylindrical or toroids with a very large radius of curvature. However, the small aspect ratio of tokamaks, the fact that the center of the plasma may not be the geometrical center in the toroid, and the fact that the plasma may not be completely circular all combine to produce a complex flux profile in the poloidal

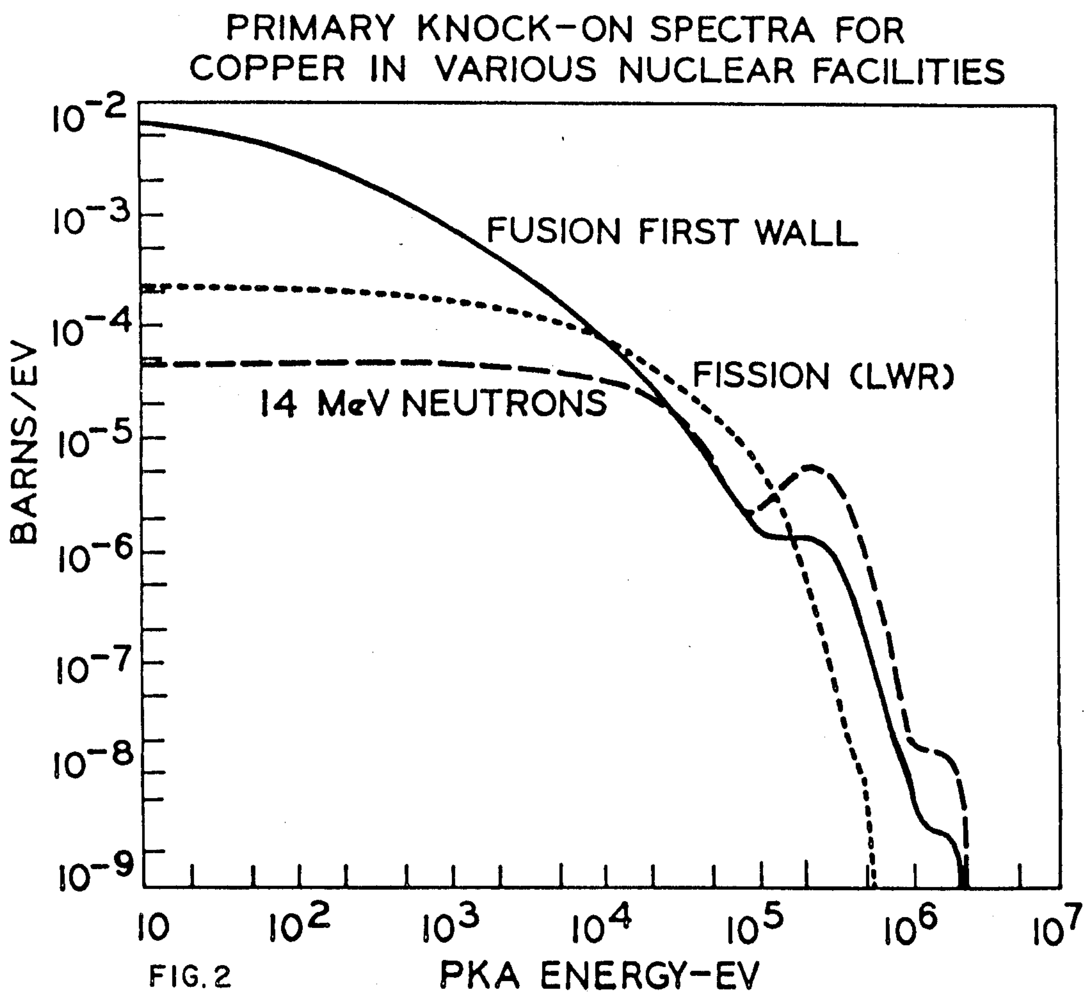

PRIMARY KNOCK-ON SPECTRA FOR
COPPER IN VARIOUS NUCLEAR FACILITIES
BARNS/EV
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
FUSION FIRST WALL
FISSION (LWR)
14 MeV NEUTRONS
10
102
103
104
105
106
107
PKA ENERGY-EV

FIG. 2

direction.[23,24] A typical example is shown in Figure 3 where the wall loading* is given as a function of poloidal angle inside the cross section of a torus for the UWMAK-III reactor.[25] In this particular example (except for the divertor slots), the maximum to minimum wall loading is ~2 and the maximum to average ratio is 1.2. Such a variation is further complicated by a back scattered neutron spectrum which also varies around the poloidal direction.

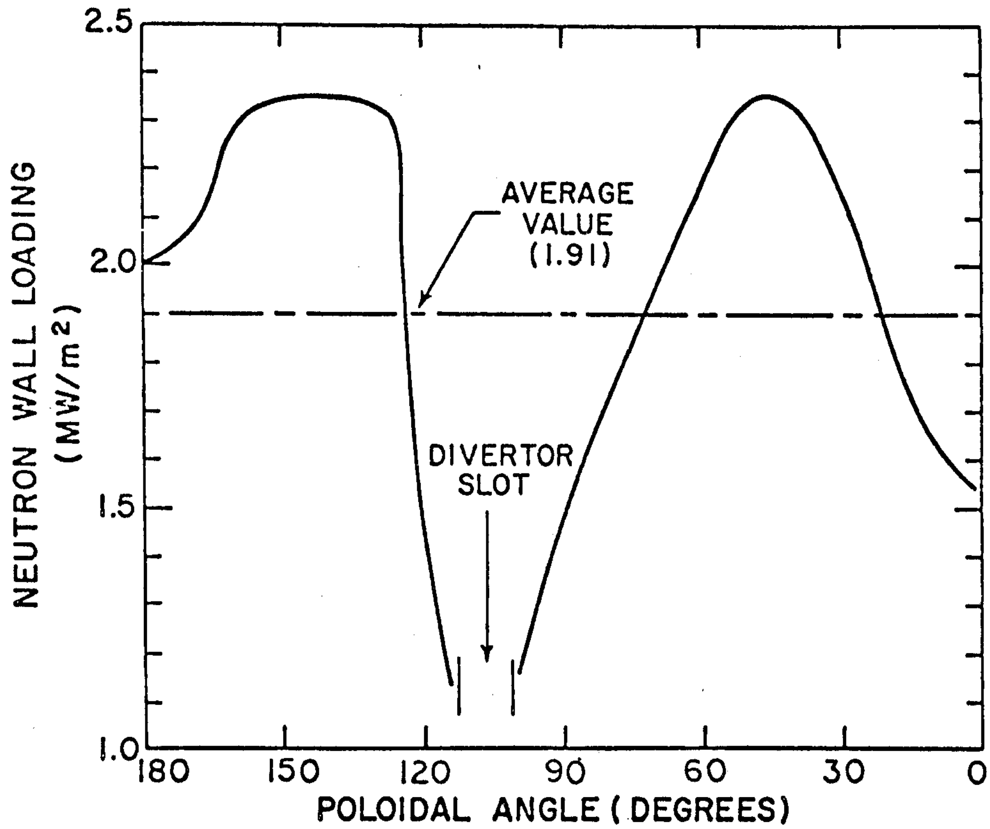
The investigation of toroidal neutronics effects is rather new at this writing but it seems certain to complicate matters for damage predictions in tokamaks. We shall see later that severe displacement damage and transmutation gradients will exist in 3 dimensions throughout blanket structure. This is in contrast to essentially 1 dimensional effects in spherical and cylindrical geometries. The analysis of such damage structures in tokamaks will also be more difficult than in fission reactor cores where there is generally a 2 dimensional geometry.

DISPLACEMENT DAMAGE CONSIDERATIONS

A somewhat imperfect, but more reasonable way of comparing the potential damage rates in fission and fusion reactors is to calculate the theoretical fraction of atoms displaced per unit time of exposure in the irradiation environment. This unit, called the dpa for displacements per atom, does not include transmutation effects or the amount of spontaneous and thermal recombination of the point defects. However, it does account for the probability that reactions will take place initially and the amount of energy which will eventually be transferred to the lattice atoms in nuclear encounters. Several authors have reported displacement cross sections[22,26-28] and we have plotted some representative values in Figure 4. Note that 14 MeV neutrons have damage energies which are ~4 times those of 1 MeV neutrons and that the absolute magnitude of the dpa cross section for heavy elements differ by less than 20%. The situation for the low Z elements (e.g. C, Al) is somewhat different in that there is relatively little difference between 14 MeV and 1 MeV neutrons with respect to dpa values. This results from the

*Defined here as the uncollided 14 MeV neutron flux/4.43 x 10^{13} n/cm^2/s.

Figure 3
Poloidal Variation of Neutron Wall Loading in UWMAK-III



predominance of low angle scattering and the low threshold for ionization losses in these elements. Such an effect means that, neglecting the spatial distribution of defects on a microscopic scale and transmutations, 1 MeV neutrons are nearly as damaging as 14 MeV neutrons and fission reactors probably make good simulation devices for displacement damage in low Z elements.

Coupling the dpa cross sections of Figure 4 with the neutron spectrum from a low aspect tokamak reactor like UWMAK-III [24], we can illustrate the macroscopic spatial distribution of damage in a tokamak reactor. The poloidal variation of dpa damage in the outer blanket is shown in Figure 5 and the variation in dpa with distance from the front wall is shown in Figure 6. Note that the maximum to average dpa values are close to, but not quite the same as the uncollided neutron flux due to the spectral effects mentioned earlier. It is also shown, in Figure 6, that the variation in dpa rates in the inner and outer blankets are different due to geometric consideration and different materials in each blanket of UWMAK-III. Note that displacement damage is reduced by ~1000 in 120 cm of blanket and reflector regions.

Another use of dpa calculations has to do with the calculation of the damage rates in various fusion concepts. For example, we know that the dpa rates in tokamaks are $\sim 10^{-7}$ dpa/sec per MW/m^2 and roughly the same for mirror reactors. However, the <u>instantaneous</u> dpa rates in a theta pinch are ~10 times higher, and those in a laser system are $\sim 10^6$ times higher. This situation (and the variation thoughout a ~1 meter blanket model) are summarized in Figure 7 for 316 SS. The displacement rates in the EBR-II reactor are also included in Figure 7 and it can be seen that they are higher than all of the values for the tokamak but actually an order of magnitude lower than those in theta pinch first walls and 5 orders of magnitude smaller than in laser (or E beam) fusion reactor blankets.

The effect of damage rates on physical processes such as void formation, creep rates, fatigue, etc.,is not very well known at the present time. It can be dangerous to think that one is simulating pulsed damage in a fission reactor which can in fact produce the desired total dpa levels but only in a steady state fashion. We should be sensitive not only to the

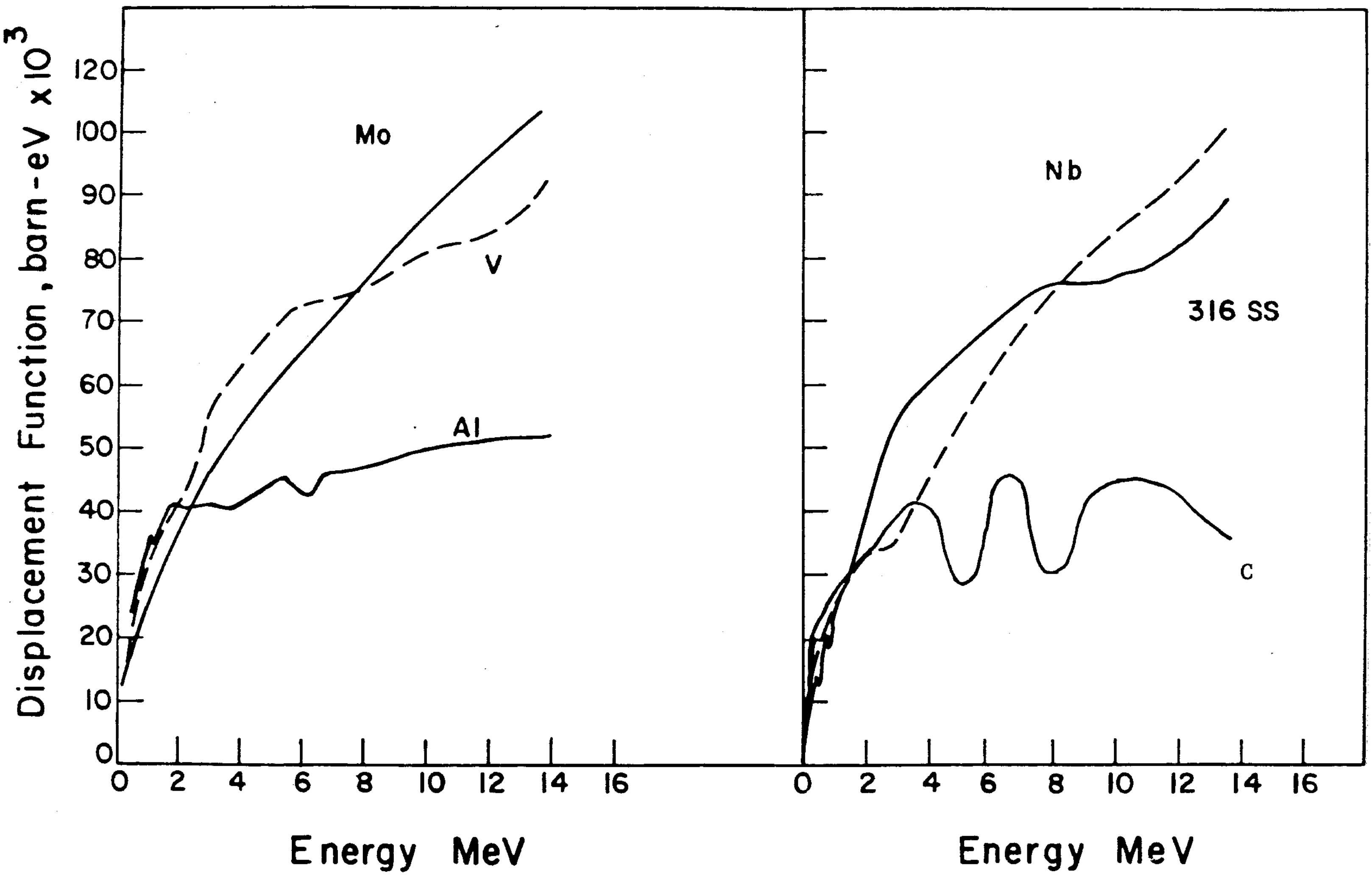
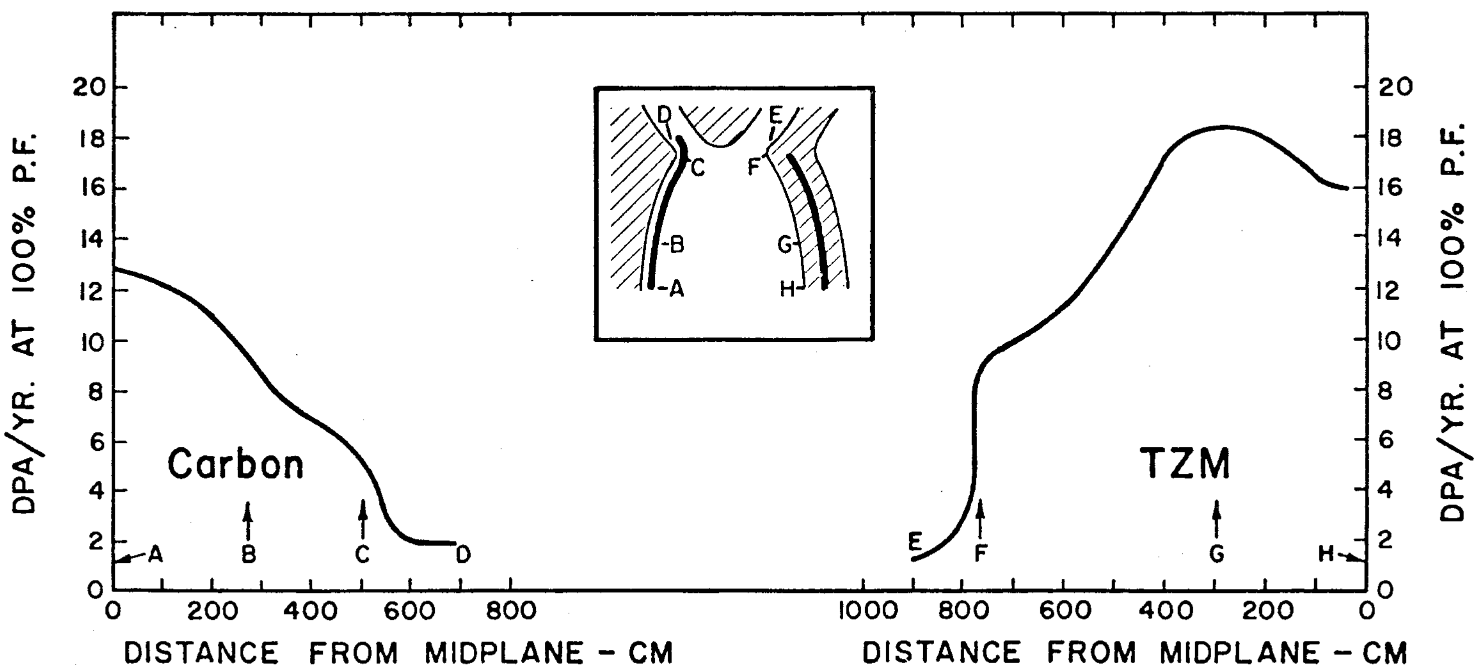


Figure 4 Displacement Function Values for Various CTR Materials

Figure 5

Poloidal Variation in Displacement Rate in the Tokamak Reactor - UWMAK-III



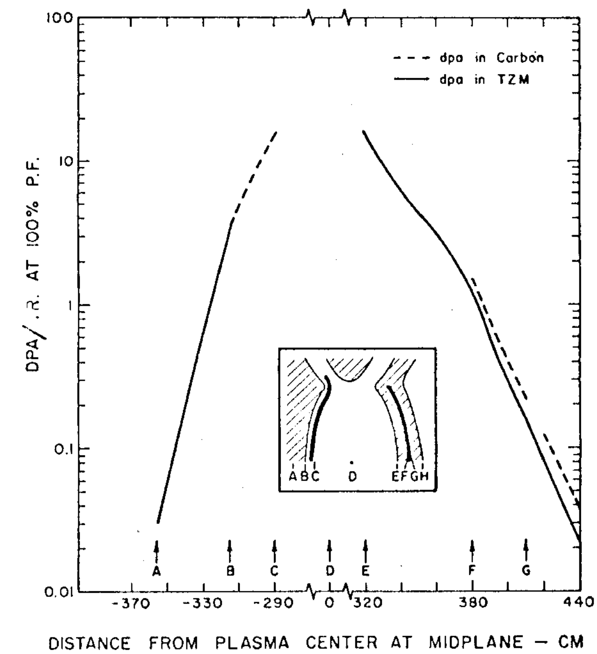


Fig. 6 - Variation of Displacement Damage in the UWMAK-III Tokamak Reactor

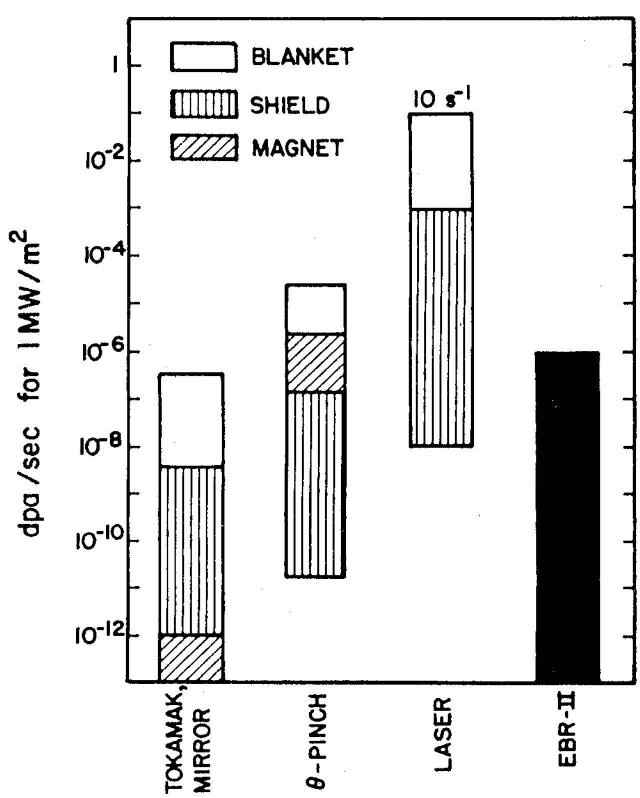


Fig. 7 - Instantaneous Neutron Displacement Rates in DT CTR First Walls

fact that some instantaneous dpa rates in fusion reactors are 10^5 to 10^6 higher than in fission reactors but also that some are actually a factor of 10 or more lower. (i.e. tokamak blankets, shields, magnets).

Recent theoretical work[29-31] shows that not only does the rate of producing damage alter such phenomena as the nucleation and growth of voids but these phenomena are also quite sensitive to the downtime (annealing time) between pulses. At the present time, there are no acceptable facilities in the world to test even the most simple of the rate theories, let alone try to incorporate the effects of the thermally induced stresses. The laser and E beam reactor concepts are the most vulnerable in this respect and a whole new field of radiation damage theories need to be developed for these concepts.

TRANSMUTATIONS

Because of the higher neutron energy in D-T fusion reactors there are a much larger variety of transmutation reactions which can take place than in a fission spectrum. We will first explore some typical transmutation rates in potential CTR materials normalized to 1 MW/m^2 wall loading, then comment on how the transmutation and displacement damage is related and finally show how the reaction rates might vary with position in a fusion blanket.

There have been several comprehensive studies on the production of gaseous and non-gaseous isotopes in CTR materials.[12,16,21,23,32,33] We will try to sumarize those results for both categories here and place them in perspective to the problems at hand. It is fairly well accepted that gaseous atoms, in particular, helium, present the greatest problem to the long term mechanical integrity of metal components. We have listed typical helium production rates in Mo, Nb, V, Al, C, and 315 SS in Table 4 for both a 1 MW/m^2 CTR spectrum and in a thermal fission reactor core. It is evident from this table that even at modest wall loadings, tens to thousands of atomic parts per million of helium can be produced per year of operation in fusion reactors. Such rates are 20-200 times higher than in fission reactors. We shall see later that at high temperatures (~0.45 to 0.5 T_m) even a few parts per million of helium can significantly reduce the ductility of metals such that safe operation can no longer be assured. Therefore, aside from corrosion, it is reasonable to assume that the upper temperature limit for structural material will be limited by this type of embrittlement and those metals which produce the greatest amount of helium will have the shortest lives in a reactor if operated at the same high temperature limit.

One point which is often neglected in this area is a consideration of the contribution of impurities to the gas generation, especially if those impurities are low atomic numbers with low coulomb barriers (e.g. Li, C, O, N, Al, Ti). This effect can be amply illustrated by three examples:

- Pure Nb versus Nb + 2000 wtppm oxygen
- Pure Al versus Sintered Aluminum Powder (Al + Al_2O_3)
- "Pure" 316 stainless steel and a commercial grade alloy.

The helium production rates of these six systems in the same neutron flux are given in Table 5. Such calculations reveal that in a metal like Nb, where the annual helium production is only ~24 appm/yr, the addition of 2000 wtppm oxygen (presumably by contamination) could increase the helium production rate by 50%. Vanadium would be somewhat less sensitive to this effect because it has a higher intrinsic helium production rate (but probably the same contamination potential). The addition of oxygen to aluminum has a significant strengthening effect but the oxygen is also a potential helium producer and actually contributes twice the number of helium atoms than would the aluminum atoms it replaces. Even in a relatively complex alloy like 316 SS we find that normal commercial impurities can increase the helium production rate by ~10-15%. It is also worthwhile to point out that there is another source of helium in fusion environments, that is, the decay of tritium absorbed into the structural material. A brief example will illustrate this point. Table 6 lists the helium produced in two positions of a fusion blanket at 1 MW/m^2, the solubility of tritium at a typical operating temperature, and the amount of helium produced by the decay of that tritium. It is evident from this type of consideration that Nb and V are very susceptible to helium embrittlement in the absence of neutron irradiation and such a phenomena may pose a serious problem for ex-reactor components such as heat exchangers which presumably would never "see" a neutron.

Table 4

Helium Production Rates in Various Potential CTR Materials

	appm/year[a]	
	Fusion[b]	Fission[c]
Mo	47	2
Nb	24	1
V	57	0.3
Al	330	8
316 SS	210	5
C	3000	34

(a) 100% P.F., See Reference 21.

(b) UWMAK-I Spectrum (16), 1 MW/ m^2.

(c) EBR-II Spectrum (15).

Table 5

Effect of Alloying Elements or Impurities on the Helium Production Rates in Selected CTR Materials

System	appm He/year at 100% PF and 1 MW/m_2
Nb	24
Nb + 2000 wtppm O	36
Al	365
SAP(10 Wt % Al_2O_3)	410
316 SS (pure)	210
316 SS (commercial)	235

It is now appropriate to consider the relationship between helium gas and displacement damage because it is not a function of flux (with the exception of Ni containing alloys) but only of neutron spectrum. A convenient method of assessing this relationship is to quote the ratio of gas atoms produced divided by the number of displacements produced in the same unit of time. Such a ratio is given in Table 7 for a fast reactor, a thermal reactor, a 14 MeV neutron source, a D-Li stripping source, and the first wall in a fusion reactor.*

The data in Table 7 is very important to consider when one is analyzing data from non-fusion facilities. The synergism between helium and displacement damage is not well understood, but it is well established. For example, high helium contents can increase swelling at the same dpa level especially at high temperatures.[34] It is known that voids do not even form in some metals during ion bombardment unless helium is present.[35] It is also known that helium introduced by the tritium trick does have a greater effect on the mechanical properties as does helium introduced along with some displacement damage.[36] Therefore, it is extremely important that experimenters who propose to simulate CTR damage in non-CTR devices take this synergism into account before making any conclusions about the viability, or lack of viability of CTR materials.

One last point to make on this ratio is that it will change as a function of distance in spherical and cylindrical geometries and in a poloidal sense as well for tokamaks. This is illustrated in Figure 8a and 8b where we have plotted the appm He/dpa ratio for Mo through a typical blanket. Note that even at 100 cm from the first wall the helium tc dpa ratios for a fusion device are much higher than in a fission reactor. (Figure 8a and Table 7) An additional feature in the fact that this ratio can vary by a factor of 2 or more as one progresses around the poloidal angle of a tokamak reactor. Hence, the designer is going to be faced with a very complex damage situation which will require data at not only various temperatures, stresses,

* We have chosen the tokamak, UWMAK-III, for this comparison.[24]

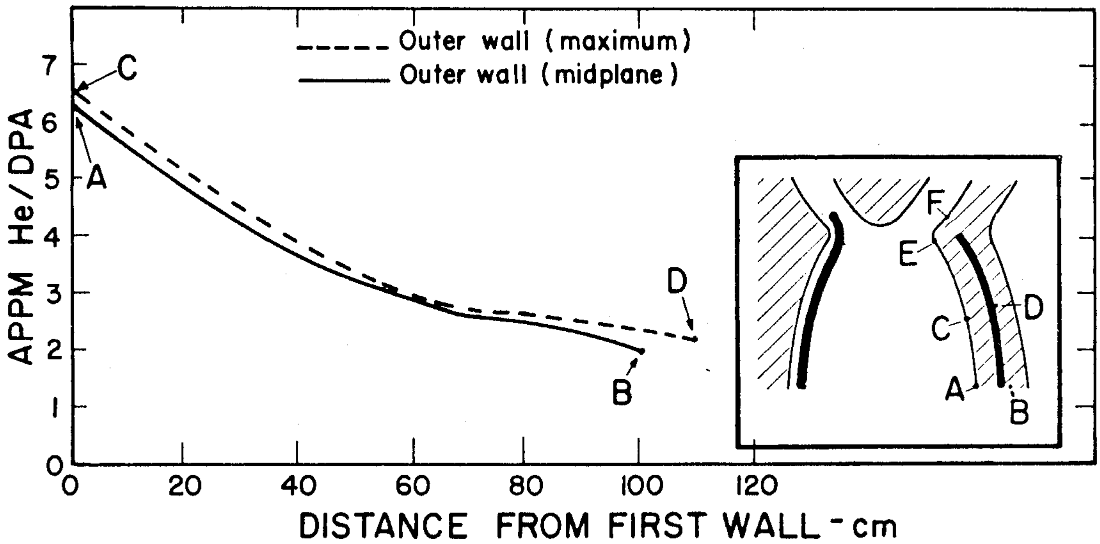


Fig. 8a - Variation in Helium Production to Displacement Ratio in UWMAK-III in the Radial Direction

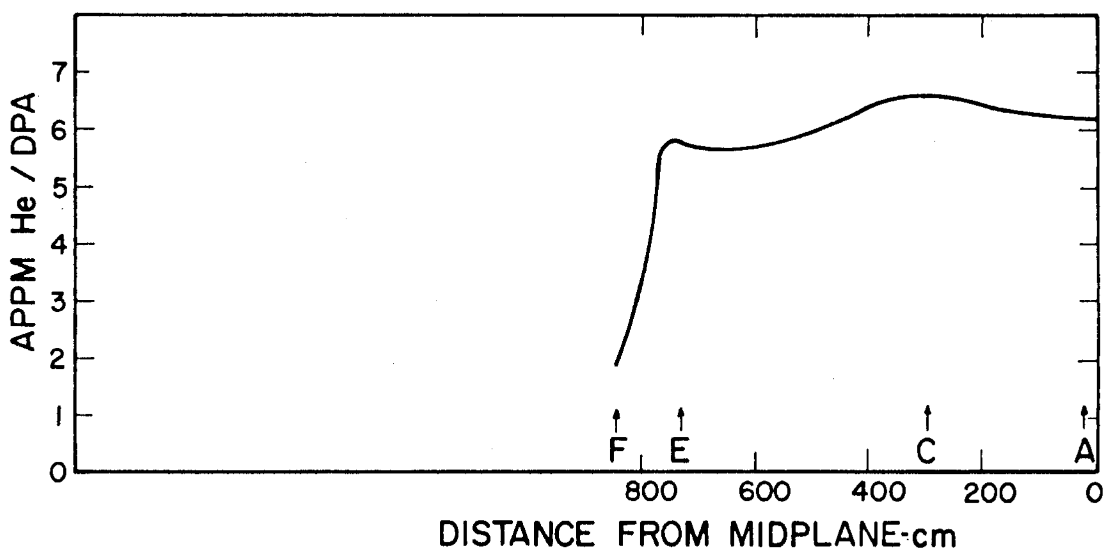


Fig. 8b - Variation in Helium Production to Displacement Ratio in the First Wall of UWMAK-III in the Poloidal Direction

Table 6

Effect of Absorbed Tritium on the Helium Production Rate in Fusion Reactors

System	appm He/yr Neutronic (a)	Typical Ave. Operating Temp. °C	appm He/yr from T_2 decay (b)	Total appm He/yr
Nb - 1st Wall	24	800	23	47
-20 cm from 1st Wall	~ 10	800	23	33
Mo - 1st Wall	47	800	< 0.01	47
V - 1st Wall	57	600	11	68
-20 cm from 1st Wall	23	600	11	34
Al - 1st Wall	365	200	<<0.01	365
316 SS - 1st Wall	210	500-600	<0.1	210

(a) For typical neutron spectrum - UWMAK-I[16]

(b) Assuming wall absorbs the tritium to its solubility limit at the average operating temperature.

Table 7

Calculated Helium Gas to Dpa Ratio for Various Nuclear Systems

System	appm He/dpa				
	LWR (HFIR)	LMFBR (FFTF)	14 Mev Neutrons (RTNS)	D-Li (BNL) (a)	CTR (b) 1st Wall
Nb	0.073	0.033	5.4	2.5	3.3
V	0.009	0.004	9.7		4.9
Mo	0.012	0.05			5.8
Al	0.31	0.11	63		24
316SS	95 (c)	0.096	36		21

(a) BNL-20159, July 1975

(b) Ref. 24

(c) Ref. 21, after 1 year of irradiation coolant environments, and damage levels, but at various ratios of gas atom production to displaced atoms. This will undoubtedly increase the cost of research and number of specimens that need to be examined before one can achieve the same level of confidence about a material's performance that we currently have about materials in fission reactors.

Solid Transmutation Effects

This is a very difficult area to treat in a limited discussion and the importance of such transmutations are just now being discovered. The calculation of the transmutation rates is a tedious procedure involving complex multiple reactions and decay chain considerations. However, Sung and Vogelsang[38] have devised a reasonable calculational procedure and we will quote a few of their results here.

Table 8 lists the largest transmutation rates of the host element to a different element in units of appm per year per MW/m^2, or amys for short. The major problem for Nb is the production of Zr at the rate of 700 amys. This element has a maximum solubility over the full operating temperature range of approximately 10% which could present problems if the neutron exposure exceeded 140 $MW\text{-}yrs/m^2$.

There are no serious problems with Mo except for perhaps Tc-99. The phase diagram for this system has not been established and should be investigated before any long term use of Mo is contemplated.

The generation of Si in Al could have serious consequence once the neutron exposure exceeded 2 $MW\text{-}yrs/m^2$. After that fluence, the Si would precipitate and could cause the aluminum to be brittle.

Finally, there does not appear to be any solubility problems for 316 SS but the generation of Mn, V and Ti might cause slight changes in the mechanical properties of the steel. The behaviour of this alloy is so complex that is is difficult to anticipate what effects such changes will have but experimental studies would not be difficult to perform on unirradiated 316 SS.

The synergistic effects of displacement damage, gas atom production and solid impurity atom generation need more careful study. Simple phase diagrams produced under equilibrium conditions may not be applicable to the irradiation state of a fusion reactor. If this is so, we had better know this well in advance of committing large sums of money to develop any particular metals industry (i.e. Nb or V) specifically for the production of fusion power.

SPECIFIC PROBLEMS ALREADY IDENTIFIED IN DT FUSION REACTOR DESIGNS

It will not be possible to discuss, in this paper, all of the problems related to bulk radiation damage that have been identified thus far. However, we will attempt to mention what we think are the most important problems and try to show how they may effect the normal operation of a fusion plant. It is convenient to discuss them in three separate groups; dimensional stability, mechanical properties and physical properties.

Dimensional Stability

As with most complex devices, close tolerances and high quality assurance will be required to assemble a fusion reactor. Once in operation it will be important that these dimensions are closely maintained for vacuum tightness and to prevent the generation of unreasonable stresses. Because of the sheer size of fusion devices (i.e. 1-2 square meters of surface area for every MW_e generated) even small percentage changes can result in large dimensional variations. In the UWMAK series of tokamak reactors, one finds that a 0.1% dimension change on the outer blanket structure can result in a 10 cm change in circumference. While the structure would have to be built to accomodate such strains (which might easily be imposed by thermal expansion) it is obvious that additional expansions or contractions, which may be a function of time, will be extremely difficult to predict, accomodate, and control.

Swelling Due to Voids

There is one major dimensional instability associated with metals when they are irradiated approximately 25-55% of their melting point. The generation vacancies at temperatures above which they are mobile and the preferential absorption of the associated interstitials at dislocations produces a situation where the vacancies become highly supersaturated and tend to precipitate into voids. The metals then decrease in density with the net result that significant swelling can occur. Values up to 50% have been reported for steels. This phenomena is rather general as shown in Table 9 where we list some of the materials in which voids have been observed. Unfortunately, Table 9 includes all the potential CTR materials proposed for fusion applications so that one must prudently plan on some limited swelling if the irradiation temperature is high enough and if the damage level exceeds a few dpa. The exact magnitude of swelling to be expected may be found elsewhere from fission neutron studies[39,40] and in many papers of this conference. The basic questions for fusion reactor designers with regard to voids in metals are the following:

- What level of uniform swelling can be tolerated without compromising the vacuum integrity, or causing the flow of coolant to be reduced?
- What level of non-uniform (remember the dpa gradients) swelling can tolerated in a fusion blanket without compromising the safe operation of that reactor?
- What effect will high helium generation rates have on the data already obtained from fission reactor studies?
- What effect will lower (tokamak and mirror reactors) or higher (theta pinch, E beam, or laser reactors) dpa rates have on the nucleation and growth or voids (compared to fission reactors)?
- What effect will periodic "anneals" between burns have on the resulting microstructure?
- What effect will the solid transmutation products have in the formation of voids?

and finally,

- What effect will stress and/or the cyclic application of stress have on the resulting propensity to form voids?

None of the above questions have been satisfactorily solved or even addressed in some cases. Such gaps in our knowledge will be very costly and time consuming to fill.

Table 8

Major Chemical Changes in CTR Materials
Due to Transmutations

System	Tranmutation	appm / Yr-Mw/m^2	Approx. At. % Solubility at 0.4 Tm
Al	Mg	400	4
	Si	40	0.1
316SS	Mn	1200	60
	V	200	20
	Ti	50	~3
V	Cr	130	S. Soln
	Ti	80	70
Nb	Zr	700	10
Mo	Tc	400	?
	Ru	30	?

Table 9

Metals and Alloys in Which Neutron-Produced
Voids Have Been Observed After High
Temperature Irradiation

Pure Metals	Alloys
Al	2024-Al, 6061-Al,
Cu	
Fe	304, 316, 321, 347, 348 Stainless Steel
Ni	NiAl, Ni-Cu, Incoloy, Inconel
V	V-Ti, V-Cu-Ti
Nb	Nb-1Zr,
Mo	TZM, Mo-0.5 Ti
Ta	
W	
Pt	
Co	
Mg	

Swelling Due to Gas Bubbles

The generation of insoluble gases (in this particular case, He) inside of metals at high temperature has been known to promote bubble formation and dimensional changes associated with that phenomena. This is not too serious in most metals (except for perhaps steels and Al) because the amount of gas generated is relatively low. On the other hand, there are certain materials which have been proposed for non-structural applications in fusion devices which could have serious problems with bubbles. Some of these include, Be, B_4C, C, and Li compounds such as Li_2O, $LiAlO_2$, or $LiSiO_2$ for example. Table 10 lists the helium generation rate in these materials at different positions in a typical fusion blanket. The important points to note are the very high helium generation rates, several thousand to >15,000 appm per year at the first wall. The B_4C is unlikely to be that close to the first wall except in special "burner" designs so that values at approximately 100 cm are more appropriate. Even at that spacing, several thousand ppm of helium would be generated per year of operation.

The effect of such high helium contents on the dimensional stability can be estimated as a function of bubble size and temperature from the following expression

$$\frac{\Delta V}{V_o} \% = 100\ N\ [\frac{rkT}{2\gamma} + b]$$

where N = number of gas atoms cm^{-3}

r = bubble radius

T = temperature

k = Boltzmann constant

γ = surface energy

b = Vander Waals constant

One can get an idea of how serious this problem might be by calculating the swelling in $LiAlO_2$ after one year of UWMAK-II exposure. Figure 9 shows that even if the gas atoms collect relatively few vacancies, swelling values of ~10% might be the characteristic after 1 year. Since $LiAlO_2$ is not a structural component but rather contained in cans, a

Table 10

Summary of Helium Production Rates in Non-Structural CTR Materials

Material	appm/year for 1 MW/m^2 Wall Loading[a]
Be	3050
C	2760
B_4C	3600[b]
$LiAlO_2$	15,500

(a) Use UWMAK-III Reactor, 100% P.F., maximum

(b) In Shield 100 cm from First Wall

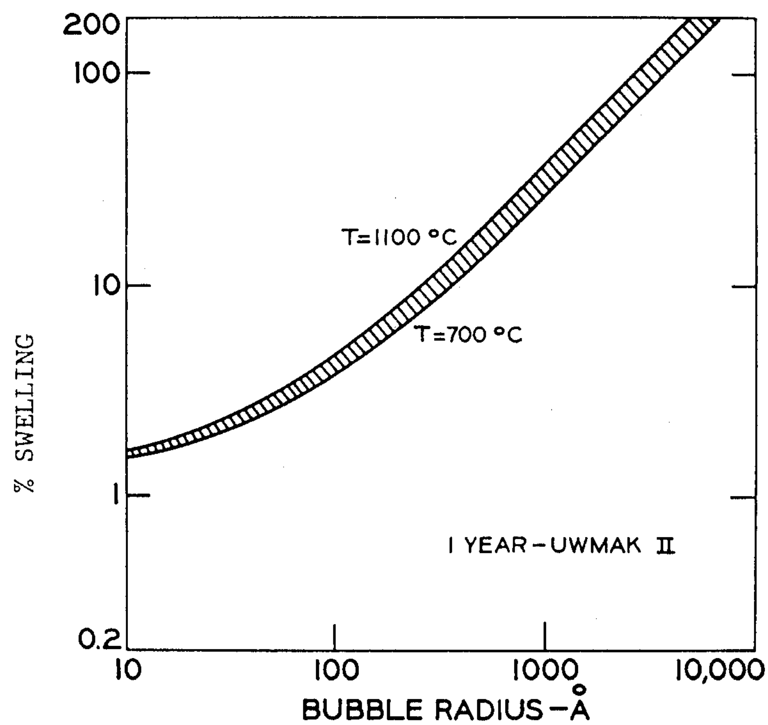


Fig. 9 – Calculated Effect of Bubble Size Temperature and Irradiation Time on the Helium Gas Induced Swelling in $LiAlO_2$

reasonable amount of dimensional instability can be tolerated. Values of 10% are not unreasonable but values of 50% may be out of the question. Such a consideration and the desire to achieve at least a one year life lifetime limits the maximum size bubble in the materials to:

	Calculated Bubble Diameter Limit for 1 year life and 50% swelling - Å
Be	10,000
B_4C	8,000
$LiAlO_2$	2,000

Previous studies in Be detected bubbles of up to 20,000 Å in dia. at 600°C and ~100 appm He.[41] Therefore, it appears that the use of Be, $LiAlO_2$ and perhaps carbon near the front walls of a D-T power reactor should be closely scrutinized. Even using B_4C closer than about 80 cm seems unadvisable above 700°C.

Dimension Change Due to Sintering

This effect would occur in CTR components which are formed by powder metallurgy techniques such as solid lithium compounds or B_4C. The main point here is that irradiation promoted sintering could initially reduce the available void space before gas bubble swelling takes place. A classic case of this phenomena is the sintering of ceramic UO_2 fuel pellets causing a shortening of the fuel column in a LWR and eventually allowing cladding collapse due to external pressures. Similar problems might arise in CTR's, especially if high pressure helium is used as a coolant.

The irradiation induced sintering also may obviate the low tritium inventory advantage that solid Li compound breeders appear to have. Because of the low diffusivity that tritium has in these compounds, they are fabricated with extremely small particle sizes (~tens of microns in diameter) to reduce the diffusion path (ℓ) the surface from where it can be collected by a carrier gas. The design philosophy is evident from the following equation

$$\text{Tritium inventory} \propto \frac{\ell^2}{D(T)}$$

Due to the low thermal conductivity of Li ceramics the temperature profile in a breeding rod (or spherical particle) can be approximated by a parabola. (See Figure 10). When the temperature is high enough for T_2 diffusion, then there is also a tendency for sintering which increases the diffusion path. Hence, it is not clear how the inventory might change (increasing or decreasing) with temperature.

The major questions (aside from gas induced swelling) that materials scientists must answer with respect to solid breeders are:

- How does a large temperature gradient effect the overall tritium inventory?
- What effect will irradiation have on the sintering rate at high temperatures?

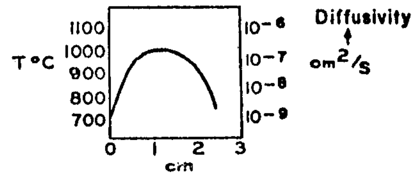
Other questions which need to be answered include,

- What happens in a pulsed reactor during the short, intense pulses, or - What sort of shock resistance is required to prevent fracturing?

Growth

With the increased use of carbon in D-T fusion reactors for (1) impurity control, [8] (2) radiation damage reduction, [43-45] (3) and neutron reflection, it is important to understand the nature of irradiation induced growth mechanism in that material. There have been several reviews on the effects of fission neutron irradiation on the dimensional stability of graphite[46-47] and even a few assessments of how this data might be translated to fusion reactors.[48-50] In general, neutron irradiation of carbon at elevated temperatures initially causes some shrinkage followed by expansion which eventually approaches a "run away" rate. Some typical data on nuclear grade graphite is shown in Figure 11. The purpose of calibrations, 1.4×10^{21} n/cm^2 (fission) is equal to 1 dpa. This figure shows that useful lifetimes

TYPICAL TEMPERATURE PROFILE IN $LiAlO_2$
AND POSSIBLE EFFECT OF SINTERING
ON TRITIUM INVENTORY IN UWMAK-II (12)



TRITIUM INVENTORY AT UNIFORM TEMPERATURE–g

AVERAGE PARTICLE RADIUS	800 °C	900 °C	1000 °C
10 μ	0.4	0.040	0.003
100 μ	40	4	0.3
1 mm	4000	400	30

Fig. 10 - Typical Temperature Profiles in $LiAlO_2$ and Possible Effect of Sintering on Tritium Inventory in UWMAK-II

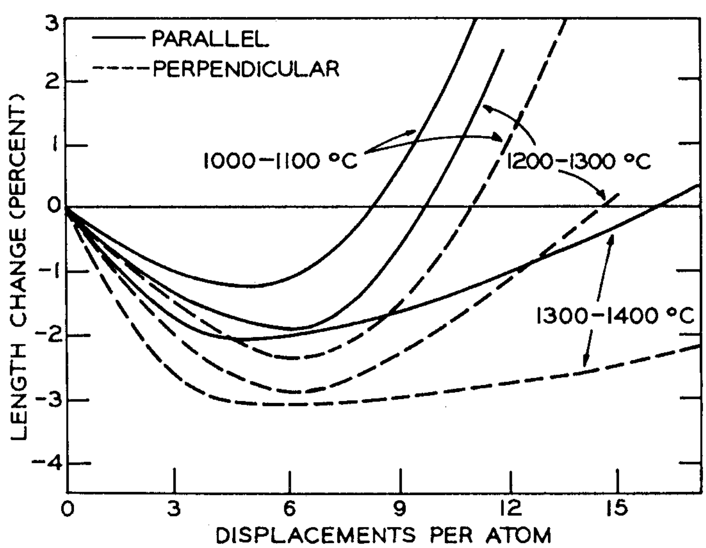


Fig. 11 - Effect of Molding Direction on Length Changes of 9640 Type Graphite

are typically 10-20 dpa at high temperatures (1000-1400^{o}C).

Figure 12 shows the present status of experimental data from fission reactors. Also included in that figure are damage-temperature regimes that might be required for reflectors, plasma shields, or neutron spectral shifters. Note that current fission data (available from fission reactor graphite) is sufficient to almost cover the needs of the reflectors. However, only limited data is available for 1200-1400°C carbon curtain concepts (roughly 2 years of equivalent dpa levels) and there is no data available for the very high temperature ISSEC concepts.[43-45] Such information must be generated before these ideas can be implemented into real reactor designs. Intuitively, one might think that as the irradiation temperature is raised above 1300°C the increased annealing would reduce the residual damage. However, a recent paper by Van Den Berg et al.[51] suggests that such a trend may not be correct and in fact they are increasing damage rates up to 1400°C. These results are at odds with the data in Figure 11 and the bulk of previous studies on graphite. Therefore, careful research is needed to understand this mystery.

It should also be stressed that form of carbon used for fusion reactors may be considerably different that those tested for fusion reactor applications. Carbon cloths,[8] and three dimensional weaves,[8] and solid carbon walls[43-45,52] have all been proposed. The reactions of these forms of carbon to high temperature neutron irradiation may be considerably different than for fuel particle coatings (pyrocarbons), or anisotropic graphite extruded forms. A whole new irradiation program will be required to address these materials and methods (which are largely unknown now) must be found to correctly simulate CTR conditions until suitable CTR neutron test facilities can be built.

Mechanical Property Changes that Could be Important in CTR Materials

This is again one of those areas wich is extremely difficult to summarize in the limited space available here. To be complete one should cover irradiation effects on such properties as,

yield strength
ultimate strength
total elongation

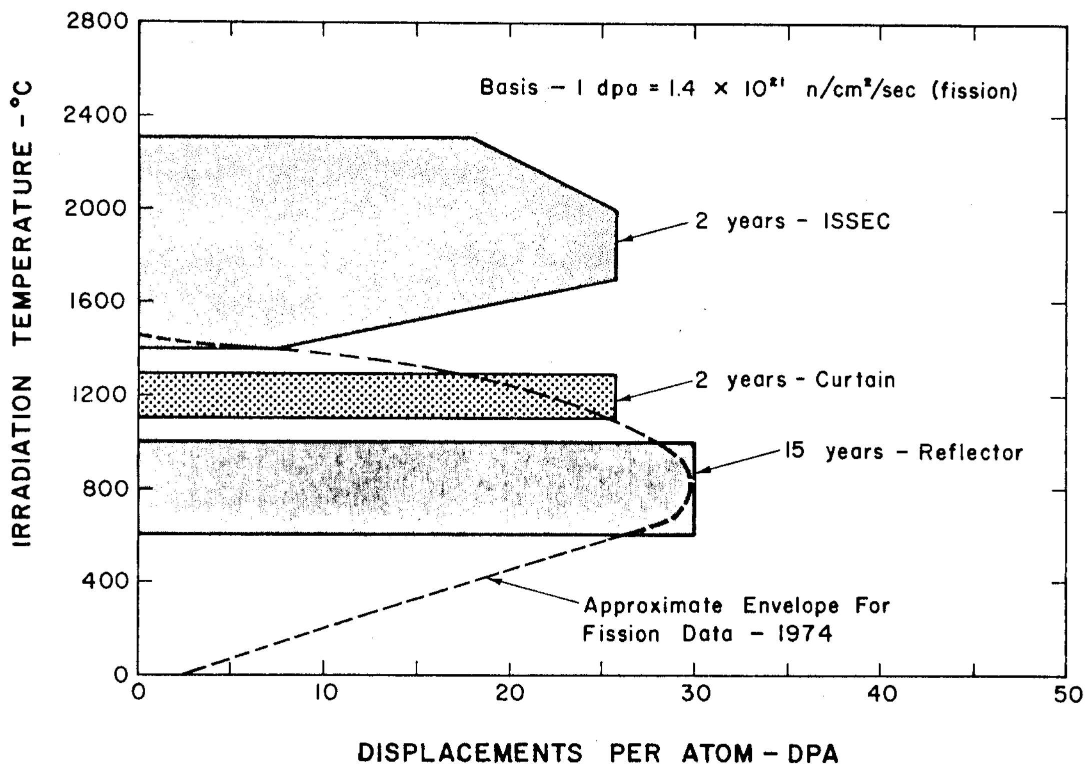


Fig. 12 - Comparison of Required Irradiation Data for Carbon in UWMAK-III to Data Available from Fission Reactors

uniform elongation
ductile to brittle transition temperatures
fracture toughness
creep
fatigue

While all of these properties are important, we will try to briefly relate uniform elongation, creep, and fatigue to the performance of a fusion reactor.

Ductility

It is absolutely essential that any massive structure such as a fusion reactor have the ability to absorb a certain amount of strain energy without plastic yielding or fracturing. This will be required to offset thermal expansion between burn cycles, finite amounts of non-uniform swelling, or simple fabrication defects. The fact that the reactor will be extremely radioactive and therefore inaccessible except for remote techniques and the high cost of having a whole power plant off the line because a single component failure means that the designers will need as big a "safety margin" as possible to keep the plant running. It is not easy to establish what that margin will be until a very detailed reactor design is available. However, we can take some lessons from the LMFBR program where it is determined that when the properties of the fuel cladding are degraded such that more than 0.4% strains will exceed the uniform elongation limit, then the component must be changed. It would be naive to simply assume the same limit applies to say a first wall of a fusion reactor which must maintain absolute vacuum tightness over a 1000 m^2 in the face of changing magnetic fields, temperatures, flow rates, damage rates, and environments. The probabilities for failure are greater and the time required to correct the fault will be longer in fusion reactors than that required to pull out a defected fuel element in a fission reactor. Intuitively, we would expect the design limit of a fusion reactor would be much more liberal than for a fission reactor, perhaps as high as 1% uniform elongation, but no one can say with certainty what it might be today.

There is only one metallic structural material for which we have enough data to estimate what neutron irradiation at elevated temperature might do to the uniform elongation. That material is 316 SS. There is fast reactor data up to ~10 dpa (only a few appm He) at temperatures up to 650°C. This data is plotted in Figure 13. It can be seen from this information that operation up to ~20 dpa would result in U. E. values of ~0.5%. This is hard data (without the appropriate helium however) to show that the 1% limit would be reached in only a few years of 1 MW/m^2 exposure.

A very fine experiment has been conducted at ORNL to establish the effect of very high helium (~several thousand appm), high dpa (up to ~90) and high temperatures (up to 650°C) on the uniform elongation of 316 SS.[53] These results are displayed in Figure 13 also. Unfortunately, the data shows considerable scatter with some data points predicting 0.5% ductility at He levels of <50 appm He at 575°C and others showing the same or better ductility at ~90 dpa and 6000 appm He. Therefore, it is difficult to establish a definite wall life unless one were to use the most pessimistic data. Such an approach would yield 2-3 months life in a reactor like UWMAK-II. If one uses the 1% U. E. design limit, then the situation becomes much worse. In fact, it is quite possible that the wall life would be <2 years even with the optimistic data. Above 650°C there is essentially no ductility remaining after 90 dpa and 6000 appm.

The whole point of this exercise is to point out again that the high helium generation rate will probably place an upper temperature limit on the first wall life irregardless of the corrosion or straight creep behavior of the material. Secondly, it says that even for the only material we have data on, the choice of design limit can only change an impossible situation (wall life <2 months) into a difficult one (wall life of only a few years) depending on the assumptions of tolerable ductility.

No such information on high helium contents exists for the other engineering materials (Al, Mo, Nb, V, etc.) because there is no corresponding quirk of nature such as the large thermal (n,α) cross section for Ni-59 in the other metals.[20] Therefore, we must again come up with, as to now, unknown techniques for testing these materials to provide a back up for the only material on which we have some high helium content data. It is not a very comfortable position to be in and could require a great acceleration of the construction of D-T neutron source facilities in order to solve the problem.

Potential Creep Problems in D-T Fusion Reactors

As with any new energy source, fusion must demonstrate, among other things, that it can produce energy cheaper and with less environmental impact than fossil fuels and fission reactors. The desire for high efficiency normally means high temperatures and each new design of a fusion reactor pushes its structural material to the stress limit. It is well known that the combination of high temperatures (close to half the melting point) and high stresses will cause materials to plastically deform over long periods of time. It has also been recently demonstrated that a superposition of neutron irradiation can increase the deformation (creep) rate over the thermal values.[54] Hence, all three ingredients required for gross deformation are present in a fusion reactor blanket and we should expect that creep rupture lifes of candidate materials will have to be further lowered over their unirradiated values (Fig. 14).

Bloom and Wiffen[53] have found that creep rupture lives of 316 SS were reduced 50% compared to their non-irradiated values and there is no particular reason to expect that this would be different with the refractory metals. Therefore, if we want to have at least 2 year wall lifes (~17,000 hr) then stresses should be <10,000 psi in stainless steel. When appropriate safety factors are included (i.e. factors of ~2) then it is questionable whether a material like 316 stainless steel can withstand the thermally induced stresses in the first walls.

Even if the first walls and coolant pipes did not rupture, deformation of 0.5% may significantly complicate the maintenance procedures. For example, current reactor designs rely on periodic changing of the first walls due to radiation damage. This requires that modules can be easily removed and replaced remotely. A 0.5% shape deformation (e.g. 5 mm in a 1 meter long panel) may cause first wall panels to "stick" or make insertion of a new one an impossible job.

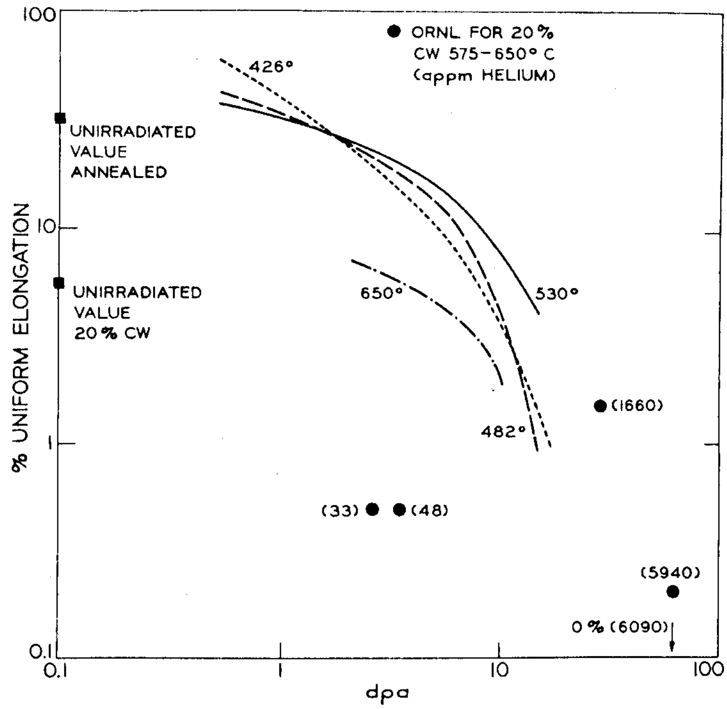


Fig. 13 - Effect of Neutron Damage on Uniform Elongation of 316 SS

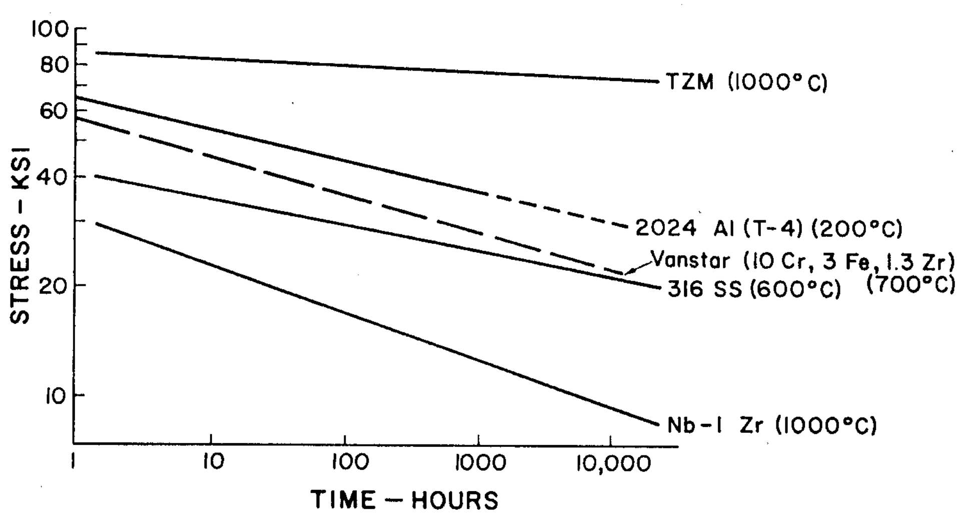


Fig. 14 - Rupture Properties of Various CTR Alloys

Since, at the present time, there is absolutely no irradiation creep data during 14 MeV neutron bombardment of any material, one must ask the following questions and set up research programs to answer these questions.

- What will be acceptable creep levels in tokamak, mirror, theta pinch E beam and laser reactors?
- What is the effect of dpa rate (from $\sim 10^{-7}$/sec steady state to $\sim 10^{-5}$ and 10^{-1}/sec instantaneously in pulsed systems) on the thermal creep rate in potential CTR metals and alloys?
- Will the high helium generation rate associated with fusion significantly reduce the creep rate in metals?
- What effect will solid transmutation products have on creep rates?
- How much of a safety factor ought one apply to creep-rupture lives (once they are determined) for fusion reactors materials where down times to replace failed components could be much longer and more expensive than in fission reactors?

One last comment on the generation of data to answer the above questions. It is relatively worthless to spend a great deal of money on post irradiation creep studies. Of all the critical mechanical properties, this one should be measured in-situ. Unfortunately, there are very few fission reactors where even one position in the core is instrumented to perform such tests. The costs of capsule design and associated equipment is also quite expensive such that the cost per data point is truly enormous. A successful irradiation creep study program needs first of all a realistic neutron source (there are none at this writing except for perhaps thermal neutron reactors for Ni containing alloys), secondly, large sums of research money (a million dollars for a capsule associated equipment and personnel for a few months of testing of one material is not unreasonable), thirdly, years of time are required to cover all the experimental conditions and materials. Such a program has not even begun as of 1975 and may represent a severe bottleneck to high power reactors (e.g. FERF or EPR) operation in 1985.

Fatigue, Perhaps the Achilles Heel of Pulsed Fusion Reactor Concepts

Fatigue, like creep is recognized by everyone as a potential problem for fusion reactors. Unfortunately, we know even less about the basic mechanisms of fatigue and the effect of irradiation on it than we do about creep, and there is even less data.

It is fairly clear where the fatigue problems stem from in tokamaks (5000-10,000 pulses per year), theta pinches (2-3 million pulses per year) or laser and E beam reactors (30-300 million pulses per year). These stresses and strains are inherent in the plasma physics of the concept and only the mirror has the potential for relatively steady state operation. Unfortunately, the quantitative stress and strain cycles for these reactor concepts have not been clearly defined so a detailed analysis of this problem can not be made today.

Finally, the data for fatigue lives should come from in-situ tests or tests which closely resemble the operating conditions of particular reactor concepts. Such tests will again be costly, time consuming and difficult to simulate using non-fusion neutron sources. There is very little LMFBR or LWR data to build on here in contrast to the case for creep, ductility, void swelling, growth, etc. Theoretical background is almost completely lacking and standards for conducting and assessing irradiation fatigue tests are largely unknown. In short, there is a long way to go in this area and lack of success in it could prevent some fusion concepts from ever surpassing the proof of principle phase.

Some Physical Properties of CTR Materials that Depend on Radiation Damage

Most all of the physical (and thermal) properties of CTR materials will change somewhat because of 14 MeV neutron bombardment. However, only a few of them have been identified as significant (perhaps because only a few have been investigated with fission neutrons, let alone 14 MeV neutrons.) We will make only a few comments here and fully expect that research in the next few years will uncover new problems and perhaps some solutions.

Electrical Resistivity

This property is mainly important for insulators and only of marginal importance for metals. A comprehensive review of the state of the art has been recently released[56] and concluded that (1) there is a general lack of data on in-situ resistivity changes for fission neutron bombardment and a complete lack of data for 14 MeV neutrons. (2) Isotropic crystal structures seem to be less susceptible to property degradation then highly anisotropic structures, (3) rate effects have not been established and (4) no information is available on the effects of high helium contents or generation of solid transmutation products.

Electrical insulators are absolutely necessary for theta pinch reactors to prevent excessive power loss in the first walls. Mirrors and tokamaks also will require insulators for neutral beam injectors or pellet injectors. It is not clear how much of a neutron exposure these insulators will experience because there may be a possibility of some shielding or placing line of sight insulators far back into the blanket where they would intercept a relatively small solid angle. There may be another insulator requirement for tokamaks if they use RF heating. Filling the wave guides with dielectrics can significantly reduce their size but such effects as high temperature gradients in thick insulator blocks remain to be investigated.[24]

The field of irradiation effects on dielectrics by high energy neutrons is not very well established or coordinated, certainly not at the level required for full fusion reactor development. Theories are essentially non-existant for the effects of helium (important because most insulators contains oxygen which has a high (n,α) cross section) on the dielectric strength. Lack of appropriate neutron sources and in-situ facilities greatly hamper a successful program in this area.

The electrical resistivity of metals is important in that one would not like to have large power dissipations in the first walls of tokamaks or theta pinches during the burn cycle. This is also true for the walls of waveguides in RF cavities. There is little high temperature-high fluence resistivity data available from fission facilities and again, none from higher neutron facilities. Moteff et al.[57] have measured the post radiation resisitivty increase in Mo irradiated to 10^{22} n/cm^2 at temperatures from 400-1200°C. It was found that at that exposure level, the irradiation induced resistivity increase was <1 micro-ohm-cm which is <3% of the electrical resistance due to thermal vibration at 1000°C. Hence, it appears that the production of voids and dislocation loops at these exposures does not cause an unmangeable resistance increase.

One word of caution before we leave this area, the electrical resistivity of metals at high temperature should be subject to transmutations and these are not adequately simulated by fission neutrons. Doping studies (in the absence of irradiation) may help understand these effects.

Radiation Damage to Superconducting Magnet Materials

This problem, which is peculiar to fusion, luckily is solvable by increased shielding in the case of tokamaks and mirrors. Of course, this means higher capital costs and adversely affects the economics of fusion power. Hence, a relatively straightforward compromise between damage to magnets and cost of increased shielding and larger magnets will have to be made in these reactors.

The radiation damage susceptibility of at least five materials will have to be examined for superconducting magnets as they are now envisioned:

Super insulation (e.g. mylar)
Structural material (e.g. austenitic steel or Al alloys)
Stabilizer (e.g. Cu or Al)
Superconductor (e.g. NbTi or Nb_3Sn)
Electrical insulator (e.g. epoxy)

Previous analysis of these problems reveals that the super insulation and stabilizer are the most sensitive to radiation effects and A15 compounds like

Nb_3Sn follow closely behind. NbTi has a rather good resistance to property degradation as will be shown later.

The problem with organics such as mylar is that they become brittle and crumble. They could lose the ability to uniformly cover the cold magnets and hence result in larger refrigeration losses. Thresholds for observable effects are in the 10^7 Rad range and a 25% reduction in ductility occurs at 10^8 Rads.[58] A recent analysis[24] of a tokamak reactor shows that a 1.5 meter blanket'leaks'$<10^6$ rads per year obviously leaving enough lifetime for even the most pessimistic designer.

The irradiation of pure metals at liquid helium temperatures has been known for some time to cause an increase in electrical resistance of these metals. Since the main function of a stabilizer in a magnet is to temporarily carry the current without significant heating in the event that a superconducting element goes normal, the increased resistance goes counter to that objective. The rates of resistivity increase for pure Al and pure copper have been determined by Horak and Blewitt [59] and are plotted in Figure 15. Note that it requires $\sim 10^{-4}$-10^{-5} dpa before the radiation damage resistance is of the same order of magnitude as the residual resistance due to impurities, imperfections and lattice vibrations at 4.2°K. Somewhat arbitrary design considerations might state that one should remove the damage (by annealing at a higher temperature) when the irradiation induced resistance exceeds the residual resistance by 10%. To relate that to real circumstances, we quote the following blanket and shield thicknesses, and the 80% plant factor dpa rates for the three most recent UWMAK reactor designs.

	Blanket and Shield Thickness-m	dpa/year at 80% P.F.	Time to Exceed ρ_0 by 10%-yr
UWMAK-I	150	5×10^{-5}	<1
UWMAK-II	190	$<10^{-6}$	<50
UWMAK-III	130	8×10^{-6}	3 (Al)

It is obvious that the damage rate in UWMAK-II is low enough so that there is no need for periodic annealing. Slight adjustments in the thickness of the stabilizer were enough to counter the higher resistivity in UWMAK-I.[16]

The next area to consider is the effect of neutron irradiation on the critical properties of superconductors. There are usually two types of data that are reported in this regard. (1) Samples which have been irradiated at room temperature (or above) and then tested at liquid helium temperatures outside the reactor afterwards and (2) samples which have been irradiated at liquid helium temperatures and tested at the same temperature without intermittent warm-up to room temperature. Unfortunately, there is very little of the latter data and that which comes from the first situation is not always representative of the true damage state. Not only are there fewer defects remaining after the higher temperature irradiation, but the increased mobility at higher temperature will cause the defects to form clusters or loops which might not occur in the "real" case of irradiation at liquid helium temperature.

Two properties are of prime importance for superconductor in CTR magnets and those are the critical temperature (T_c) and the critical current density (J_c). The effects of fission neutron irradiation on the J_c of NbTi and Nb_3Sn are shown in Figure 16 as a function of displacement damage.[60] Considering the typical dpa rates* (appropriately adjusted for different atomic weights) one concluded that the J_c is changed by less than 10% for both alloys in typical fusion environments.

The effect of irradiation on the T_c of several alloys and compounds has been studied by Sweedler et al.[61] and is given in Figure 17.* For practically all the A15 compounds, a significant drop in the T_c occurs at 10^{-3} dpa. On the other hand, the NbTi is much more resistant to such degradation and should show no significant degradation until ~10^{-2} dpa (as ~1000 years of service in a UWMAK reactor).

In summary, appropriate blanket and shield design can reduce and even eliminate radiation damage as a major problem in CTR superconducting magnets. However, the price paid is the extra cost of materials and the larger magnet design. A special effort must be made to verify these trade offs in integral tests at liquid helium temperatures.

Side Effects of Transmutation in CTR Materials

The nuclear reactions that take place with potential CTR materials not only produce gas and impurity atoms, but they also produce considerable levels of radioactivity. This, in turn, causes high radiation fields

*For purposes of comparison 1 dpa ~$3\times10^{21}n/cm^2$.

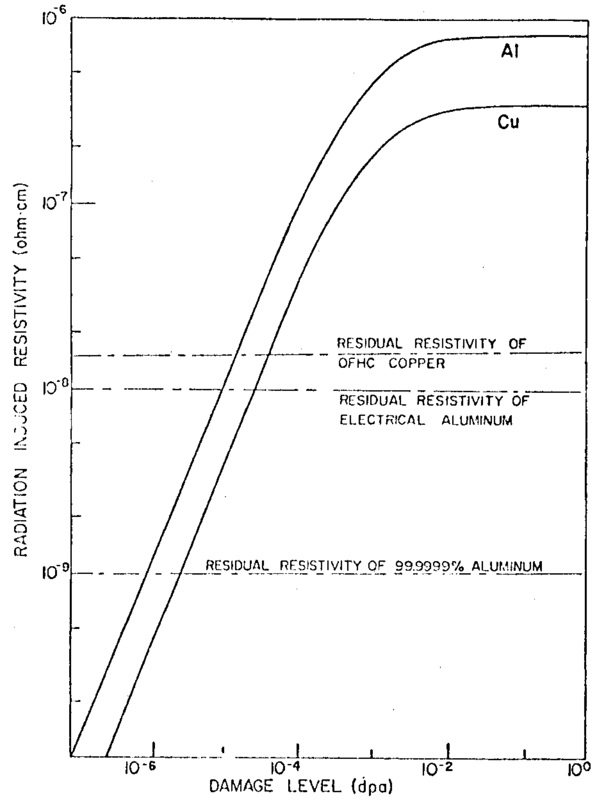


Fig. 15 - Radiation Induced Resistivity of Copper and Aluminum

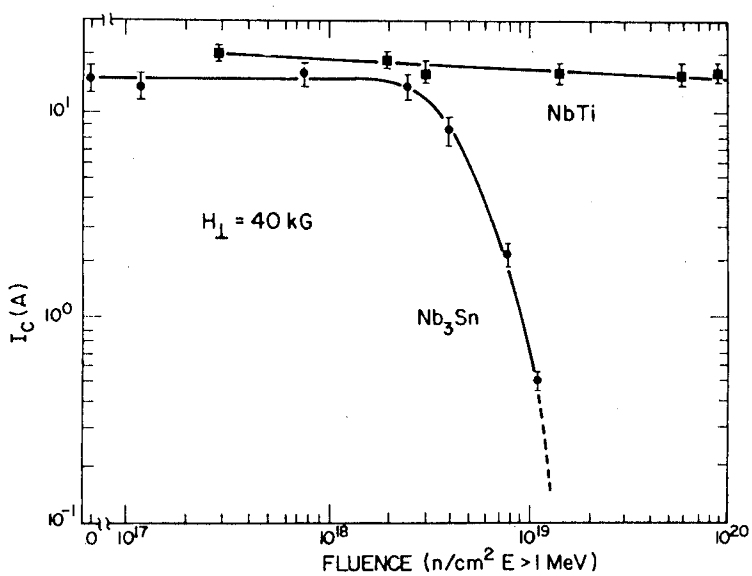


Fig. 16 - Effect of Neutron Irradiation on the Critical Current in $NbTi$ and Nb_3Sn (60)

in the vicinity of the blanket, shield and magnets such that all normal repair and maintenance must be done remotely. The activity levels for

typical CTR materials are given in Figure 18 and after two years of operation at 1 MW/m^2. The blanket configuration and total volume of material was constant in each case.[62] The first thing to note is that activities of approximately 1-5 curie/watt are typical of all materials at shutdown. Secondly, the decay of the radioactivity is fastest for the Al and V alloys, followed by Nb-Ti, TZM and 316 SS in that order. It appears that a significant amount of radioactivity will be removed a few days after shutdown such that radiation levels in Al and V systems might be "tolerable."* Unfortunately, this does not continue indefinitely and saturation occurs in some metal systems because of long lived isotopes. The major isotopes which contribute to the short and long lived activity of these metals are given in Tables 11 and 12 for reference. Contrary to popular opinion, the reader will see that there is a considerable amount of radioactivity associated with D-T fusion and society must get used to the fact that there will be some long lived isotopes which must be stored and protected from release long after fusion plants are closed.

The decay of this radioactivity causes a great deal of heat to be generated in the metal and an example of the levels associated with the radioactivity in Figure 18 are shown in Figure 19. Note that while the value is relatively high (~50 MW_t in a 5000 MW_t plant) the energy <u>density</u> is quite low (~0.1 $watt/cm^3$). Such low values do not present a hazard for melt down even if the coolant flow, or the coolant itself is lost.[63] This conclusion appears to be true for all currently suggested CTR materials.

DISCUSSION OF THE IMPORTANCE OF NEUTRON RADIATION DAMAGE ON COMMERCIAL CTR POWER PLANTS

The degradation of materials properties by neutrons results in at least the six following major effects:

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* This merely means that with appropriate shielding and weeks of decay, one might be able to approach the reactor to perform simple hand operations on the defected components.

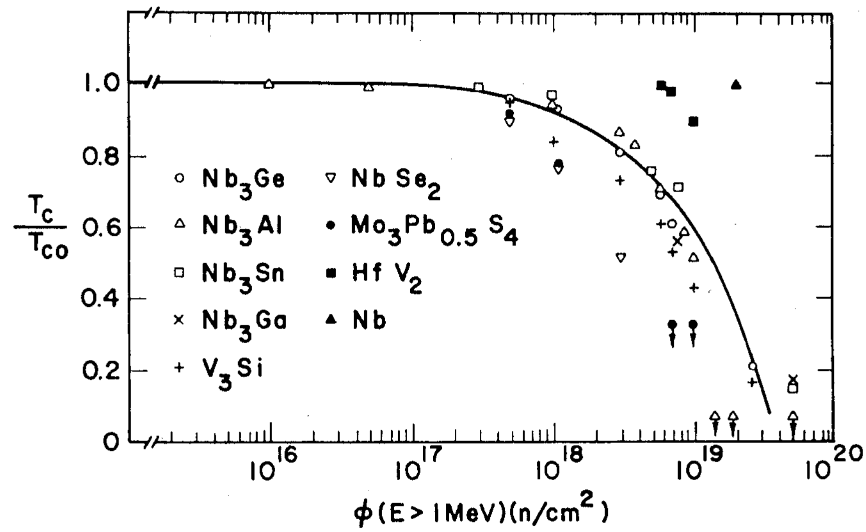

Fig. 17 - Effect of Ambient Temperature Irradiation on the Critical Temperature of Various A15 Compounds

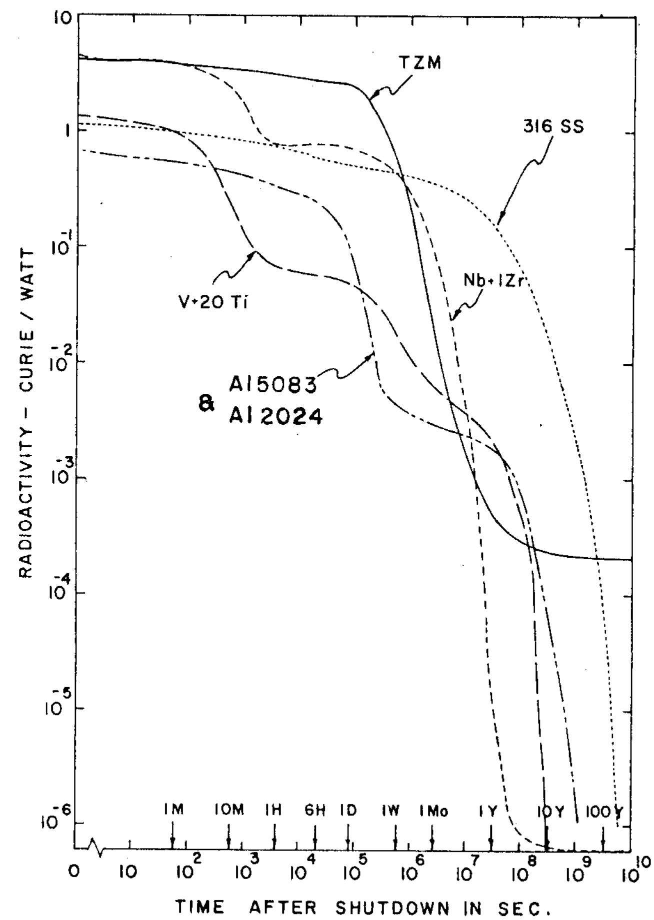

Fig. 18 - Radioactivity Induced in a CTR Blanket - 2 Year Operation - 5000 MW_t

Table 11

Summary of Major Isotopes Contributing to the Radioactivity of Potential CTR Alloys at Shutdown After 2 Years of Operation

Alloy System	Radioactive Isotope	Half-Life	Radioactivity at Shutdown (Ci/watt)
2024 Al	Na 24	15 h	.180
	Mg 27	9.5 m	.145
	Cu 64	12.8 h	.137
	Al 28	2.3 m	.0953
TZM	Mo 99/Tc 99^m	66.7 h/6 h	1.512
	Mo 101/Tc 101	14.6 m/14 m	0.441
	Mo 91	15.5 m	0.0656
	Nb 92^m	10 d	0.0213
Nb-1Zr	Nb 94^m	6.3 m	4.408
	Nb 92^m	10 d	0.720
	Nb 95	35 d	0.0168
	Y 90	64 h	0.0117
V-20 Ti	Sc 48	1.8 d	0.039
	Ti-51	6 m	0.080
	Sc-47	3.4 d	0.009
	V 52	3.8 m	1.025
316 S.S.	Mn 56	2.6 h	0.353
	Fe 55	2.6 y	0.197
	Cr 51	28 d	0.100
	Co 58	71 d	0.091

Table 12

Major Long Lived Radioisotopes in CTR Materials — 2 Yr. Operation

Major Long Lived Radioisotopes in Potential CTR Materials - 2 yr. Operation

System	Isotope	Half Life-yr.	Ci/watt at 100 yr.	BHP[(a)] at 100 yr. km^3 air/MW_t
Al-2024	Al-26	735,000	7.4×10^{-8}	0.73
316 SS	Co-60	5.2	9×10^{-9}	0.02
	Ni-63	92	1.7×10^{-5}	8.3
	Mo-93	10,000	4.2×10^{-6}	42
V-20Ti	None	----	----	----
Nb-1Zr	Sr-90	28	3×10^{-9}	0.099
	Nb-94	20,000	6×10^{-7}	0.29
TZM	Mo-93	10,000	2.1×10^{-4}	2100

(a) BHP = Biological Hazard Potential, Ci/watt divided by the maximum permissible concentration.

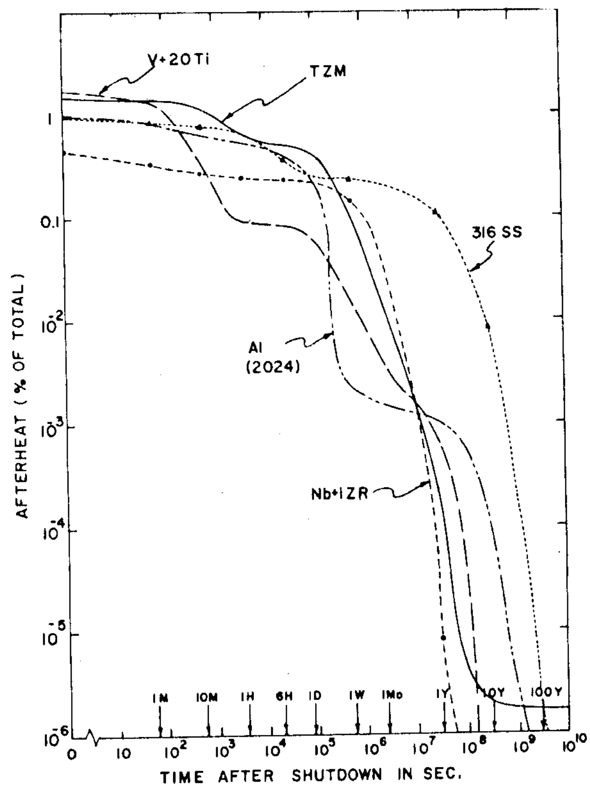

Fig. 19 - Afterheat in Potential CTR Structural Materials - 2 Year Operation - 5000 MW_t

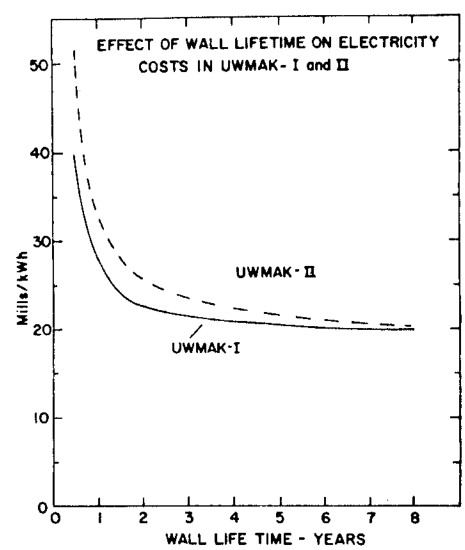

Fig. 20 - Effect of Wall Lifetime on Electricity Costs in UWMAK-I and II

(1) Reduced Efficiency - The generation of helium gas tends to reduce the maximum temperature that CTR structural, breeder and neutron multiplier materials can operate at for long periods of time. This in turn reduces allowable coolant temperatures which in turn will lower the overall plant efficiency.

(2) Reduced Plant Factors - The fact that certain components of the reactor will have to be replaced before the full lifetime of the plant is reached means that costly shutdowns must occur. The exact down time is a function of many complex considerations but some perspective on the costs can be obtained if one remembers that the revenue from a 2000 MW_e plant is approximately \$1,000,000 per day at 20 mills per kw-hr. Estimates for some reactor designs predict approximately 30 days per year may be lost due to radiation damage and changing the first walls costs approximately 30 million dollars per year per 2000 MW_e plant in down time alone [64].

(3) Increased Capital Costs - Spare modules need to be purchased at the start of the plant to replace those involved in the first change out (thereafter the costs are included in operating costs). Increased remote handling equipment will be necessary to minimize the time involved in plant shutdown. Added hot cell facilities may also be required. Shielding requirements for gamma rays emitted from damaged components (or good ones for that matter) will also increase the overall plant costs. Waste storage facilities will have to be expanded beyond those required for components which fail for "conventional" reasons such as corrosion, machining faults, etc.

(4) Increased Operating Costs - Items 1, 2, and 3 combine with other costs to raise the cost of electricity as measured in mills per kw-hr. A rough idea of the sensitivity of this number to first wall lifetime is shown in Figure 20 [64] This analysis, which is detailed elsewhere for UWMAK-I and II, reveals that if the first wall lifetime gets to be less than 2 years (at a nominal wall loading of 1.2 MW/m^2) the average cost of electricity rises dramatically. It also shows that the increased cost of lowering the wall life from 8 to 4 MW/m^2 is only approximately 10% of the total.

(5) Increases the Volume of Radioactive Waste Which Must Be Processed and Stored - Most of the major reactor studies to date have made some assumptions about the first wall lifetime. These are listed in Table 13 along with the metal system and the amount of material that needs to be replaced per MW_e per year. This number is surprisingly constant considering the variation in design group, materials, and reactor power level. A reasonable average is approximately 0.4 metric tonnes/MW_e/year. If we ever do get into a large scale fusion reactor economy, such as 10^6 MW_e by 2020,[65] then this means that approximately 400,000 metric tonnes of radioactive waste would be generated per year. Clearly such a number represents a potential problem in waste management.

(6) Demand on Scarce Elements - When components become defective and radioactive at the same time, it is usually more economical to compact, process then store them until the radioactive decays to safe levels than try to refabricate them. However, we see from Figure 18 that the decay times can take hundreds, if not thousands of years. Hence, for all intents and purposes, the replacement of these components will have to come from new elements. The disposal of say 400,000 metric tonnes per year of 316 SS means that approximately 70,000 metric tonnes of Cr must be supplied per year along with appropriate amounts of Mn and Ni. In some cases, e.g. Be, there may be no choice but to reprocess the radioactive and contaminated metal because world reserves are not adequate for a "throw away" economy.

Even if all the components had the same life as the reactor, there would be the problem of what does one do with the radioactive structure when the plant becomes obsolete and a new one must be built. The blanket, shield, magnets, supports, and all equipment within 3 meters of the plasma will be too radioactive to dispose of in a conventional manner. These masses typically amount to approximately 50 metric tonnes/MW_e and will also place a severe our limited resources as the second, third, fourth, etc. generation plants are phased out in the 21st century.

Table 13

Summary of Radioactive Waste Amounts for Various CTR Reactor Designs

Reactor	System	Predicted Wall Life $MW\text{-}yr/m^2$	Material Replacement Metric Tonne/MW_e-yr
UWMAK-I	316SS	2.5	0.69
UWMAK-II	316SS	2.3	0.49
UWMAK-III	TZM	3.4	0.31
ORNL	Nb-1Zr	>10	0.41
BNL	Al	3.8	0.27
LASL-ANL	Nb-1Zr	10	0.33

FINAL REMARKS

This has been a rather broad look at the neutron damage problems currently envisaged for D-T reactors. Not all the problems have been discussed and indeed a whole class of conditions for fission-fusion concepts has been left out. However, it is hoped that the reader will begin to appreciate the concern of the materials science community over the growing list of problems to be solved. There will undoubtedly be more problems identified in the future. We must therefore reluctantly conclude that next to the plasma physics problems, radiation damage is the second most serious obstacle to the commercialization of fusion power.

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