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FIRST WALL ENGINEERING AND TECHNOLOGY IN FUSION

by
G. R. HOPKINS

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G.R. Hopkins
General Atomic Company
San Diego, California 92138

The first wall of a fusion reactor presents a particularly difficulty engineering design problem because of the severe environment in which it must operate, yet remain useful over a reasonable lifetime. All the plasma emanations interact with the first wall. Plasma particles cause erosion and heating, electromagnetic radiation produces heating, and neutrons cause radiation damage and potentially high radioactive material inventories. The energy partition between the radiation and particle loads has a high uncertainty at this stage of development and it would be desirable to control this for fusion power reactors. Plasma disruptions cause high pulsed heat loads, with magnitudes sufficient to melt and vaporize refractory materials. With the worst projections, first wall lifetimes would be unduly short in power reactors. With continuing attention to the disruption phenomenon, however, the experience gained in experimental power devices should provide the background for plasma boundary region control to prevent surface erosion, and to limit the number and intensity of plasma disruptions.

The First Wall

The first wall is for the purposes of this discussion, broadly defined as the first 10 mm thickness of material interfacing with the plasma in a fusion reactor. This includes the major skin surrounding the plasma, commonly referred to as the first wall, and protrusions beyond this such as limiters, armor, and mechanical divertors. Collectors for magnetic divertors may also be included since they may provide the first intersection of a flux surface with a material. The important feature is that all these components intercept some or all of the plasma emanations. Both magnetic and inertial confinement fusion concepts employ first wall components, and in some respects their requirements are similar. However, most of my remarks in this paper are directed to magnetic confinement.

The first wall operates in one of the most severe environments in a fusion reactor and a long lifetime is considered highly desirable. It interfaces directly with the plasma either in a line of sight or with a magnetic surface connecting to the plasma edge. Thus, it can be a significant source of impurities for the plasma and any mechanism which releases atoms, molecules, or particulates from the surface can contribute to impurity generation. Physical sputtering, chemical reactions and/or vaporization of materials, for example, can be large enough that lifetime limitations from surface erosion and thinning of the first wall material become of special concern.

Tritium is the major radioactive material and most costly element in the fuel cycle for fusion. Because of potential hazards for its inadvertent release, it is desirable to keep inventories small. The first wall can act counter to this through trapping of tritium particles incident on the plasma interface surface and by tritium diffusion through the first wall into the coolant circuits. The neutron flux in the first wall region is the highest in magnitude and also has the largest energy spread of all the regions in the more conventional fusion reactor designs. The first wall can then become highly radioactive through neutron interactions. The various erosion mechanisms and mass transport phenomena can spread this radioactivty from both the coolant side and plasma interface side of a first wall, creating problems in regions far removed from the primary source.

While the total energy content of the plasma is a known or specified quantity, there is a considerable latitude for control of this energy's release from the plasma. This includes partition between kinetic energy of atomic particles and electromagntic radiation, the spatial regions on the edge of the plasma where the energy emanates and, hence, is absorbed on the first wall, and the time distribution of the various forms of energy release. Both normal conditions including startup, burn, and shutdown, and abnormal

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situations such as plasma disruptions need to be taken into account. The heat fluxes tend to be higher than usually encountered in power plant technology and in the cases of tokamak disruptions and inertial confinement, time scales for pulsed energy release can be short enough to induce mechanical shock waves. Electromagnetic fields are high and can change rapidly, producing large mechanical forces through eddy current interactions.

The heating sources for these plasma particles, with a tokamak reactor as an example, are shown on the left side of Fig. 1. Ohmic heating is the primary initial heating source to establish a plasma in the device and comes from resistive losses of currents induced directly in the plasma. This energy goes first to the electrons and from there is imparted to the ions. This energy source can also produce the high energy runaway electrons some of which escape from the plasma and deposit their energy on the first wall. Neutral beam and radiofrequency (rf) heating are two auxiliary sources being considered for heating the plasma to ignition. The rf energy is mostly reflected from the first wall and is not expected to produce a significant heat load. Neutral beam heating through inefficiencies in stopping by the plasma and in untrapped particles can produce significant heat loads and high energy particle fluxes on the first wall. This is shown as beam shinethrough in Fig. 1. Other heating techniques include adiabatic compression, turbulent heating, relativistic electron beam injection, cluster injection, plasma-gun injection and laser-pellet hot plasma formation.[1] None of these are characterized well enough at this stage to firmly quantify their impact on first wall engineering in this discussion though some may produce concentrated heat loads and/or particle fluxes on the first wall.

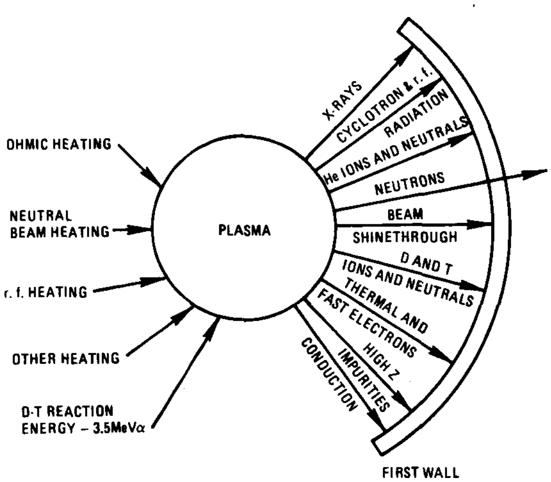


Fig. 1. Plasma energy balance

The first wall, it is seen, operates in a complex environment, in one where the information needed for a complete engineering design is not yet available. The conditions are beyond the levels of usual experience and require a continuing search for suitable materials and technology development. In this report, we will discuss first some of the quantitative aspects of the first wall environment along with some general consequences. A second part describes some specific aspects of first wall response of special interest to the author. There are many important phenomena, particularly in the effects of the first wall on the plasma as well as other system effects which are not even mentioned here. Thus no claims for completeness are made.

The First Wall Environment

The environment in which the first wall must perform is on the one hand primarily dictated by the energy balance of the plasma which it surrounds. This is the energy absorption side. The other side which may or may not be the same physical surface is, of course, the side utilized for cooling. The components of the plasma energy balance are depicted in Fig. 1. The particles which make up the plasma and are involved in this energy balance picture are electrons, deuterium and tritium fuel ions, helium ions as ash from the D-T reactions, and impurity ions.

The largest energy source in the plasma is of course from the D-T reactions which produce 14 MeV neutrons and 3.5 MeV alpha particles. The neutrons do not interact with the plasma particles, are highly penetrating, and after traversing the first wall, deposit most of their energy in the blanket. The primary interactions to be considered in the first wall are energy deposition and heat removal, and neutron radiation damage to the material resulting in lifetime limitations and induced radioactivity. In a power reactor the alpha particle helium is expected to deposit most of its energy in the plasma where it is then emitted by conduction, diffusion, and radiation. Some of the high energy alpha particles may also not be confined and thus intercept the first wall at high energy. This can exacerbate erosion through sputtering processes but is not expected to add a large heat source.

The energy output forms from the plasma are shown on the right hand side of Fig. 1, and it is the interaction of these with the first wall which is of most concern here. Note first that all except the neutrons are entirely absorbed by the first wall. Also note that there are two main forms, electromagnetic radiation and a variety of energetic particles. More detailed characteristics of these energy forms are given in Table 1 along with some properties of importance in first wall interactions. The

TABLE 1

STEADY STATE ENERGY BALANCE ON THE FIRST WALL

TYPE	ENERGY RANGE	% OF FUSION REACTION POWER[(a)]	POTENTIAL FOR EROSION	ABILITY TO DIVERT	LOCALIZATION
1. NEUTRONS	THERMAL TO 14 MeV	80	NIL	NO	NO
2. PLASMA D AND T IONS	COLD TO THERMAL	1–10	HIGH	YES	YES
3. NEUTRAL ATOMS	COLD TO THERMAL	1–5	HIGH	NO	YES
4. HELIUM IONS	COLD TO THERMAL TO 3.5 MeV	1–10	HIGH	PARTIALLY	YES
5. ELECTRONS	COLD TO THERMAL TO 100 MeV	1–10	YES	YES	YES
6. BEAM SHINETHROUGH	~100 keV	–	HIGH	NO	YES
7. IMPURITY IONS	COLD TO THERMAL	0–1	VERY HIGH	YES	YES
8. BREMSTRAHLUNG X-RAYS	1–100 keV	5–10	NO	NO	NO
9. IMPURITY RADIATION X-RAYS	1–20 keV	0–15	NO	NO	NO
10. CYCLOTRON RADIATION	MICROWAVE AND INFRARED	0–5	NO	NO	NO
11. GAMMA RAYS FROM BLANKET	1–10 MeV RANGE	–	NO	NO	NO

(a) VALUES SHOW APPROXIMATE RANGES FOR POWER INCIDENT ON THE FIRST WALL.

first seven entries are particles and entries 8-11 are electromagnetic radiation. All have the common feature of energy deposition in the first wall during normal steady state operation. The first and last entries, neutrons and gamma rays, deposit their energy within the volume of first wall material whereas the remainder produce primarily a surface heat flux. Exceptions are high energy electrons and the higher energy x-rays which may penetrate to depths comparable to first wall dimensions for low atomic number materials.

The energy ranges shown in column 2 span approximate limits and not all energies need be incident on the first wall all the time. Thermal energy range in the case of neutrons refers to blanket thermal energies ($\lesssim$ 1000°C) and in all other cases to plasma temperature (5-50 keV). The "cold" designation refers to particles in the plasma first wall boundary layer which may range from less than the plasma temperature down to equilibrium wall temperatures. The actual particle energy range of each type incident on the first wall may be a design variable to some extent, with neutrons and hydrogenic bremstrahlung as exceptions. For example, the ability to control particle energy may be very important in reducing erosion due to sputtering since the sputtering coefficient has a threshold with particle energy, below which sputtering is small.

The relative power of each of these energy forms on the first wall is shown in the third column as percent of total fusion reaction power. The fixed quantities are the reaction energy split in the plasma between neutrons 80% and helium ions 20%. In an ignited system, the helium ion energy is the primary source which is transferred to the other forms on the way to escape from the plasma. Thus the sum of actual values for entries 2 through 5 plus 7 through 10 must add to 20% for a given operating condition. The energy partition and ranges are this author's estimates and will eventually be narrowed down as a better understanding of the plasma boundary is attained for ignited plasmas. It is still expected there will be some design options remaining not only in the fraction of energy in each energy type but also in the energy spectrum within a type. It is expected that an especially important parameter will be the division between particles (not neutrons) and radiation. This will influence erosion rates, heat loads, sputtering, and the use and condition for limiters and divertors, for example. Maximum variation might be from 5% to 15% for radiation with an accompanying 15% to 5% for particles; this is a factor of three which will be significant in first wall design.

Estimates of the partition of energy between radiation and particles are available from measurements on present day tokamaks which operate with limiters. The limiters absorb most of the particle energy, and the vacuum vessels most of the radiation power. Results from a recent survey by Taylor[2] are shown in Table 2 for several devices. These include both diverted and non-diverted and both ohmic

TABLE 2

RADIATION AND PARTICLE POWER
AND ENERGY PARTITION IN TOHAMAKS

MACHINE	PARTICLES	RADIATION
	ENERGY TO LIMITER / INPUT ENERGY (TYPICAL RANGE/MAXIMUM)	POWER IN RADIATION / INPUT POWER (%) (TYPICAL RANGE/MINIMUM)
PLT	10–20%/30%	30–50%/20%
PDX (NON DIVERTED)	10–20/30	30–50/20
PDX (DIVERTED)	80–85/–	–
ISX–B	50/70	20–50/10
ALCATOR–A	10–20/–	30–40/–
D III	–	50–80/30

heated and neutral beam heated conditions. The differences are most likely due to variation in impurity content of the plasmas with higher impurities resulting in the higher radiation powers. These do illustrate a factor of 8 spread for both particles and radiation, though the uncertainties could be large. The PDX results also illustrate the ability of a divertor to limit impurities and to direct the changed particle flux away from the first wall.

Referring again to Table 1, the remaining columns show qualitatively some parameters that can affect first wall design. Erosion of the first wall from sputtering may be especially severe and require frequent replacement of the wall. Hydrogen and helium ions and atoms rank high with sputtering coefficients ranging from 0.001 to 0.01 and potentially high fluxes. Impurity ions of higher atomic number can have sputtering coefficients greater than unity, thus could potentially produce very high erosion. Electrons have the potential for local high erosion through thermal vaporization from concentrated energy deposition by runaway electrons and arcing phenomena. The "ability to divert" column shows those forms which may be directed away from the first wall to a region exterior to the plasma chamber. Thus divertors could be utilized to reduce erosion and energy deposition on the first wall, as well as reduce plasma impurities.

The localization factor refers to both the natural tendency and specially induced means for localized, non-uniform energy deposition. Neutrons and radiation are emitted isotropically and are not influenced by external means. Charged particles follow magnetic field lines and would deposit their energy on the first material interface with the flux surface. Limiters provide an example of this localization. Neutral atoms can be localized near limiters and in regions such as divertor throats where hot ions are in close proximity to the wall and charge exchange rates are high; this produces localized enhanced erosion. A design concern for local energy deposition is, of course, also the peaking factors for the heat removal requirements.

In addition to the steady state heat loads, there are several phenomena which may produce intense short time pulsed heat loads. The energy content is large enough and times short enough that localized melting of refractory materials like tungsten and vaporization of carbon may occur. There is first the well known plasma disruptions in tokamak devices where the energy content of the plasma is simply deposited on the first wall. Times for energy deposition are not well characterized but for large tokamaks may range from as short as 10 to 100 μs for phenomena dominated by the Alfvén velocity in the poloidal field[3] to 10 msec for the slower acting plasma instabilities. The Princeton PLT measurements show disruption times typically in excess of 1 msec with shorter ones quite rare. This time constant is particularly important in determining induced voltages and currents, and electromagnetic forces on first wall components. Runaway electron disruptions tend to occur on a fast time scale and also to be concentrated in energy deposition so that melted spots are produced over small areas on refractory metal limiters in present day devices. There is some expectation that runaway electron disruptions can be avoided in power reactors so that it need not be a design concern at this stage in development. In any event, techniques for energy absorption applicable to plasma disruptions should also apply.

The energy available at disruption in power reactors is nominally 200 MJ and upwards for the plasma gas particles with an additional approximately equal amount to be dissipated from the poloidal magnetic field energy.[3] It is expected that the energy deposition will be localized. The thermal energy from particles will deposit on some fraction (< 50%) of the first wall causing local heating. The deposition area of typically 100 m^2 gives 2 MJ/m^2; this gives heat fluxes ranging from 200 MW/m^2 to 2 x 10^5 MW/m^2. The effects of 2 MJ of energy deposited with these heat flux values range from simply a high temperature rise with no damage to the vaporization of significant quantities of even a refractory material like carbon. This possible range produces a wide uncertainty in design requirements.

Unipolar arcing on first wall surfaces facing the plasma is yet another localized energy deposition mechanism. Arc tracks observed on vacuum vessel surfaces in the DIII facility are typically a few millimeters long and consist of a series of craters from 2 to 80 m deep.[4] Some show melting around the crater lip. While the energy deposition is high locally, the total energy is small so that the main first wall design concern is in erosion from surfaces.

First Wall Response

An outline of the major first wall components in a toroidal tokamak reactor design is shown in Fig. 2. Three distinctive regions for energy deposition are indicated: the

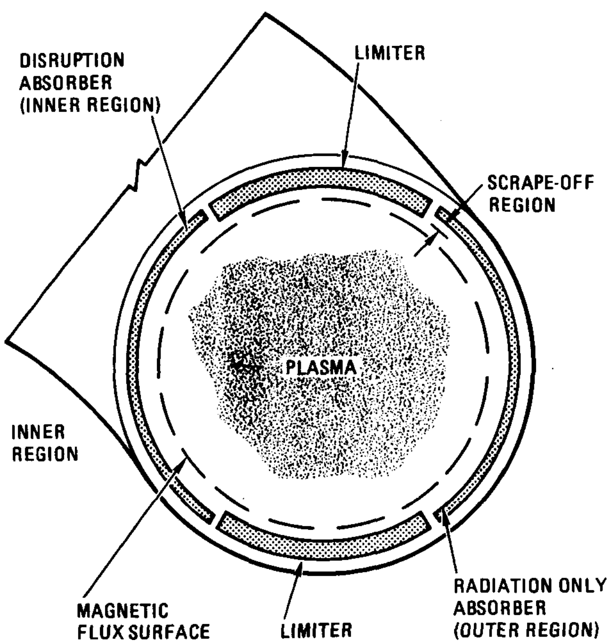


Fig. 2. Plasma chamber cross section showing first wall component placement

disruption absorber or armor on the inner region of the torus, the limiters on the upper and lower regions, and absorber where only radiation is incident on the outer region. [Note that a beam stop absorber (not shown) could be placed in a penetration of the inner region so that beam shinethrough would not add to the plasma first wall energy load.] This geometrical arrangement provides for separation of the disruptive and steady state heat loads, and the particle, radiation, and neutron first wall heat loads. Major disruptions primarily occur onto the inner region in present day devices like PLT[5,6] and designs for power reactors which retain this feature would have an advantage in the separation of pulsed and steady state energy deposition.

The limiters in this model are the first surface to intersect magnetic surfaces and thus would absorb practically all the charged particle energy flux. The energy density in the scrape-off region shown in Fig. 2 decreases exponentially with distance from the plasma with an attenuation coefficient of 1 to 4 cm in present day hydrogen devices. Ulrickson[5] has suggested that a separate attenuation coefficient is needed for each plasma species, so a power reactor might have a thicker scrape-off region. However, as long as the spacing is larger than the maximum, all ion energy would be absorbed on the limiter; neutron and plasma radiation energy would be absorbed approximately uniformly on all regions.

The heat loads and particle fluxes for the model are given in Table 3. The neutron heat deposition is volumetric in character, is not large, and for a 1 cm thick wall is typically less than the particle heat load on a limiter. It may be comparable to the radiation load in some cases. The 14 MeV neutron flux incident on the first wall is used as the major quantity for defining the power level, 1 MW/m^2 shown in Table 3, and the total spectral neutron flux is about a factor of ten times the 14 MeV value. The major effects of these neutron levels are radiation damage to the materials and induced radioactivity discussed more below.

The radiation heat load is shown for the maximum available as 20% of the fusion power. The resultant heat flux is readily handled for fusion power fluxes to 5 MW/m^2. Further, scaling down to 5% of the fusion power is, as discussed above, a reasonable lower limit. With the lowest values, the heat loads are comparable to those from neutrons.

Several parameters are included for the particle heat loads. The first row is simply based on particle balance for the plasma density, confinement time and surface to volume ratio indicated in Table 3. This gives 10^{19} particles per square meter per second. If these typically have the plasma temperature of

TABLE 3

PARTICLE AND HEAT LOADS ON THE FIRST WALL AT 1 MW/m^2 NEUTRON POWER DENSITY

SPECIES	% OF FUSION POWER	DEPOSITION LOCALIZATION FACTOR	PARTICLE ENERGY	PARTICLE FLUX	THERMAL POWER DEPOSITION
NEUTRONS	80	100%	14 MeV PLUS THERMAL SPECTRUM	$4.5 \cdot 10^{17} m^{-2} s^{-2}$ $4 \cdot 10^{18} m^{-2} s^{-1}$	$4\text{–}10\ MW \cdot m^{-3}$
RADIATION	20	100%	X RAYS	–	$0.25\ MW \cdot m^{-2}$
HYDROGENIC IONS AND ELECTRONS	2	100%	10 keV	$10^{19} m^{-2} s^{-1}$ (a)	$0.025\ MW \cdot m^{-2}$
	20	10%	10 keV	$1.5 \cdot 10^{21} m^{-2} s^{-1}$	$2.5\ MW \cdot m^{-2}$
		LIMITER ONLY	OR 1 keV	$1.5 \cdot 10^{22} m^{-2} s^{-1}$	$2.5\ MW \cdot m^{-2}$
			OR 0.1 keV	$1.5 \cdot 10^{23} m^{-2} s^{-1}$	$2.5\ MW \cdot m^{-2}$
ALPHA	<1	10% LIMITER ONLY	BROAD SPECTRUM	$4.5 \cdot 10^{18} m^{-2} s^{-1}$	SMALL

a) MINIMUM PARTICLE FLUX FOR A PLASMA DENSITY OF $2 \cdot 10^{14} cm^{-3}$, PARTICLE CONFINEMENT TIME OF 10 SEC, AND A VOLUME/SURFACE RATIO OF 0.6.

10 keV then a heat flux of 0.025 MW/m^2 for 2% of the fusion power results. Reduction of particle energy would lower the thermal power deposition. The other rows for hydrogenic ions and electrons show values based on energy balance. In this case, 20% of fusion power has been chosen as a maximum, and a limiter localization factor of 10%, yielding a heat flux of 2.5 MW/m^2. With 10 MW/m^2 as a practical upper limit for long-term operation, it is apparent that particle heat flux may be a limiting factor in first wall design. The combination of particle flux and particle energy is then calculated from energy balance. It should be noted that the particle fluxes are several orders of magnitude above the minimum required for particle balance. These particle flux magnitudes along with particle energy are the main variables for sputtering and surface erosion. Thus control within these ranges could become important.

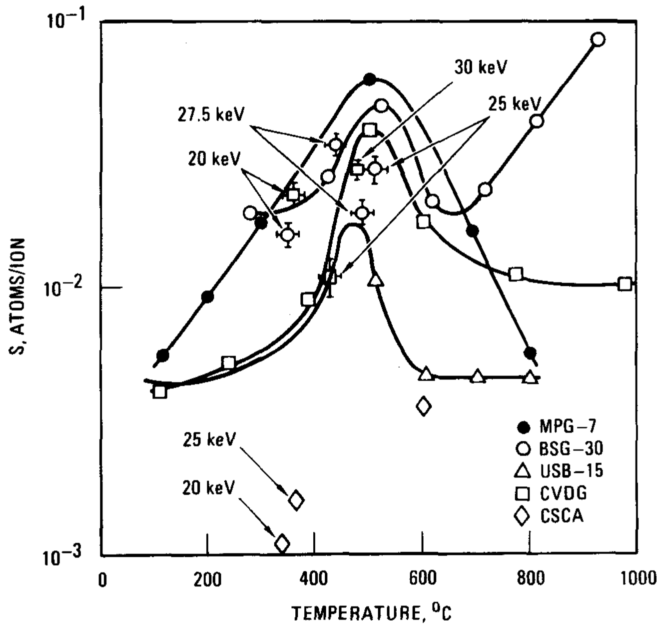
The alpha particle flux is based on particle balance with a 10% localization factor. The energy spread can range from 3.5 MeV down to complete thermalization at wall temperatures. With the flux fixed, it is the spectral distribution which is important in determining sputtering and wall erosion. Sputtering coefficients for helium may be several times larger than for hydrogen and it could become in some cases a significant contributor to wall erosion.

The problem of engineering the limiter to provide a uniform energy deposition is a significant one. In the first place, if the scrape off region is in the order of centimeters thick and follows the magnetic surfaces, then the limiter surfaces need to be positioned with respect to the magnetic surfaces to accuracies in the order of millimeters. Similar accuracies in surface contouring of the limiters are also needed. Both magnetic shimming of the fields and mechanical shimming of the limiters may be required. The penalty is localized high heat flux and erosion which could shorten the limiter lifetime. It thus may be desirable to operate in a high radiation power mode and hence low particle power condition, or employ divertors to reduce the limiter loads.

Erosion of the first wall has been identified as a major problem area for ETF[7] and the range of fluxes shown for hydrogenic ions in Table 3 can be used to estimate rates. Consider a sputtering coefficient of 0.01 and a particle flux of 1.5 x 10^{23} $m^{-2}s^{-1}$; this leads to an erosion rate of 3.0 x 10^{21} $atoms/m^2 \cdot s$ for ETF (at 2 MW/m^2 wall load). For carbon this is 0.06 grams per m^2s, or 7 x 10^{-9} m/s. This rate would remove a millimeter of limiter material every 2 days, and is at least a factor of 100 too high from an operational point of view.

The options for reducing this erosion rate are several. The flux of particles can be reduced by increasing the energy of the particles striking the wall from 0.1 keV to 10 keV, giving a factor of 100 decrease in number of particles. Sputtering rates do not change as fast with energy in this range so a net gain is achievable. If some means could be found to reduce the particle flux to only that required for plasma particle balance and spread them out to 100% of the plasma chamber surface, then reductions of 10,000 can be projected. Another option would be to reduce the particle energy below 0.1 keV to a range below sputtering thresholds; this should also provide a factor of 100 reduction. Utilization of a divertor to direct the particles away from the limiter to an external region either during all or only part of the operating cycle would also be an effective method. Finally, materials and operating conditions can be selected where the sputtering is below the value of 10^{-2} chosen in this example.

Carbon materials have been identified as providing a useful range of properties for first wall application.[8] Included are particularly high temperature strength and thermal shock resistance, low vapor pressure, and low atomic number for reducing plasma impurity effects. One problem area is the potentially high sputtering rate, approaching 0.1, due to chemical sputtering. Some recent data are shown in Fig. 3 which illustrate the main features. The first four materials listed in the caption are various forms of carbon materials and show the chemical sputtering peak around 500°C. The differences within the group which produce the variations in sputtering are not identified in detail but are presumably due to structural differences and chemical composition. Operation of a limiter at 400°C or below with these materials would keep the sputtering coefficient at ∿0.01. An additional material, the CSCA SiC-C alloy, has been measured at a few temperatures and shows a surprisingly low sputtering coefficient of 0.001 at 350°C. The reason for this is not clear. This material could be used either as a monolithic limiter material or as a coating and hopefully would alleviate some of the erosion and plasma impurity problems associated with limiters.



● MPG−7 — A HIGH STRENGTH, LOW POROSITY, HIGH PURITY GRAPHITE (U.S.S.R.)

O BSG−30 — A SILICONIZED GRAPHITE WITH BORON; 72% C, 25% Si, 3% B (U.S.S.R.)

△ USB−15 — A BORONATED GLASSY CARBON − UGLESITAL; 90% C, 5−10% B (U.S.S.R.)

□ CVDG — A HIGH DESNITY, HIGH PURITY HIGHLY ISOTROPIC CHEMICAL VAPOR DEPOSITED GRAPHITE (U.S.A. − GENERAL ATOMIC)

◇ CSCA — A CARBON-SILICON CARBIDE ALLOY; 94% CARBON, NOMINAL 6% SiC (U.S.A. − GENERAL ATOMIC)

Fig. 3. Temperature dependence of the sputtering coefficient for various forms of graphite and graphite containing materials with hydrogen ion beams (Energy = 10 keV if not shown otherwise) (see Ref. 7 for source)

The major design concern on the disruption absorber shown on the inner wall of the reactor outlined in Fig. 2 is in absorbing the high intense pulsed heat loads. The steady state heat load is from radiation and in the model here would be up to 0.25 MW/m^2 for the conditions shown in Table 3. This is not high from heat removal standards and the main effect is in determining the wall temperature at the start of the disruption. With convective cooling, this temperature may be kept arbitrarily low. Disruptions may cause severe and rapid degradation of the wall and for ease in frequent replacement, radiatively cooled plates have been proposed.[9] In this case, temperatures are determined by the steady state heat flux for the black body radiation cooling. This temperature may in fact be the limiting parameter in selecting the neutron wall power density for this design. Typically, with carbon as a plate material, 20% of the fusion energy in radiation, an 1800°C temperature limit, radiation cooling from only one side of the plate, a maximum neutron output power density of 2.6 MW/m^2 is calculated.[8] This is adequate for many of the power reactor designs which have been considered. The temperature limit here was determined from consideration of plasma impurity due to chemical reactions of hydrogen and carbon to form methane and acetylene. Other variations in design such as reducing the fraction of power in radiation, and including the radiation power loss from the front side of the plate to the colder parts of the plasma chamber would allow increases in the power density or decreases in the temperature.

The disruption energy deposition of 2 MJ/m^2 at rates of from 20 MW/m^2 to 2 x 10^5 MW/m^2 is sufficient to cause melting and vaporization of refractory materials. Surface melting may be tolerable during disruptions, however vaporization may be troublesome if the erosion rate is fast, requiring too frequent wall replacement. The temperature rise (T) during a heat pulse is given by the equation

$$\Delta T = \frac{2}{\sqrt{\pi}} \frac{q}{k} (\kappa t)^{1/2}$$

where q is the heat flux, k the thermal conductivity, t the time after start of the pulse, and κ the thermal diffusivity (equal to $k/\rho c_p$ with ρ the density and c_p the specific heat). The temperature rise is thus decreased by preventing localization, thus reducing the heat flux q, and extending the time for disruptive energy deposition. The erosion rate E for graphite from thermal vaporization is given by the equation

$$E = 1.6 \times 10^{12} T^{-1/2} \exp(-92000/T) \text{ mm/s}$$

with T in °K, and this may be used in conjunction with the time dependent temperature to estimate erosion from a pulsed heat load. The high sensitivity of erosion to peak temperature is illustrated as an example in calculations for an inertial confinement reactor chamber lined with carbon.[10] If the peak surface temperature is limited to 2800°C, the erosion is about 1 mm/yr; allowing the peak temperature to rise to 3700°C increases the erosion to about 1 m/yr and 5200°C gives 10^3 m/yr. These are all for 3×10^7 pulses. The deposition parameters range from 0.4 MJ/m^2 at 850 MW/m^2 to 1.0 MJ/m^2 at 2000 MW/m^2 for the two extreme cases. It may be concluded that disruptive events as now projected for tokamaks will in all probability cause significant vaporization of the first wall.

The TNS reactor[3] design study analyzed the design case for 2 MJ/m^2 deposited in 10 μs onto carbon. These calculations give erosion rates of 16 μm per disruption, a mass vaporized of 3.6 kg per disruption, and a total of 640 disruptions to produce a 1 cm thickness loss. The 3.6 kg seems a large amount of material to be deposited in the vacuum system and the consequences should be evaluated. In a power reactor, it would be desirable to limit disruptions to rare events if possible.

Stresses arising from thermal gradients in materials may be another limit in determining tolerable disruptive energy and power densities. Analyses for POCO graphite indicate that compressive stresses on the surface are the first to reach the yield stress and thus the limit. This would produce flaking and chiping of material. Typical limiting conditions to just produce cracking were 0.3 MJ/m^2 for a 500 μs pulse at 600 MW/m^2. This is below the range expected in tokamak disruptions so that in the present day graphite materials, stresses may be limiting rather than vaporization.

Some experimental data have been obtained on a TiC coated POCO graphite limiter material being developed for use in the DIII facility;[7] the results are shown in Fig. 4. Following exposure to the conditions indicated by the data points, the samples were examined microscopicaly, for cracking and for surface melting. The three regions where 1) no visible damage was observed, 2) where only microcracking of the TiC was observed, and 3) where both melting and microcracking of the TiC were observed are delineated on the figure. While the effects are for TiC, the data are not inconsistent with the microcracking threshold for POCO graphite of 0.3 MJ over 500 μs estimated above. The estimated power reactor disruption range of energy flux of 2 MJ/m^2 at times of 10 msec and below is shown in the upper left of the figure for comparison. One would expect microcracking to occur with a single disruption. Tests to determine multiple pulse behavior are needed but this TiC coated graphite material seems to be on the borderline of suitability.

Single pulse tests to determine a failure point for disruption absorber materials can give upper limits to tolerable energy and power densities. There are, however, many effects in

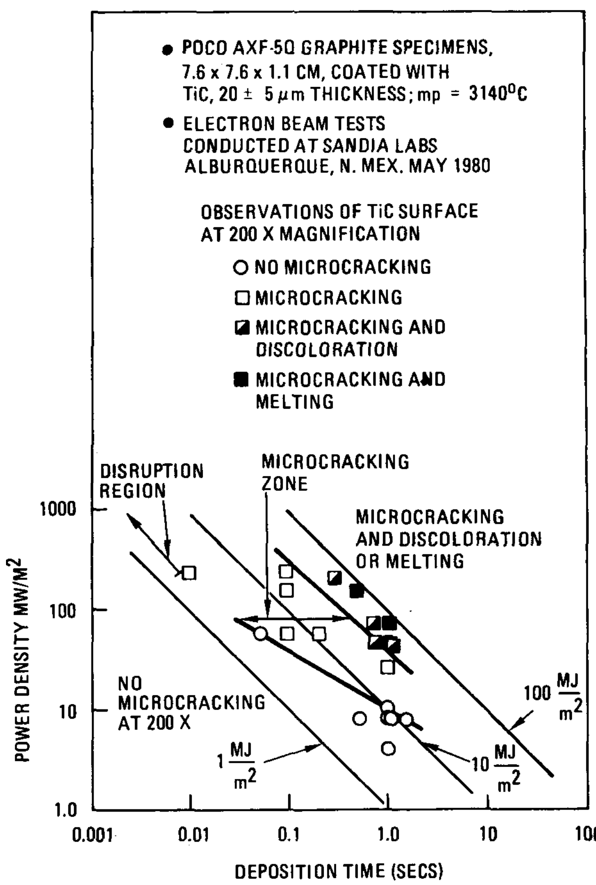


Fig. 4. Observations of microcracking and melting of TiC coating caused by electron beam depositions over an area of 1 cm x 1 cm

both metallic and ceramic materials which occur with repetitive cyclic stresses that could limit both the levels and numbers of disruptive energy loads considerably below the single pulse stress level. Fatigue, endurance limit, crack growth in metals and slow crack growth in ceramics are phenomena which need to be factored into design.

Neutron Interactions

The ability of neutrons to modify the thermal, mechanical and physical properties of materials is a subject much discussed under the general term radiation damage. Spectral differences between fission and fusion neutrons can be quantified and neutron interaction rates for most processes and materials can be calculated. While the production of atomic displacements in the lattice structure of materials can be calculated, the effects of these on material properties can be reliably determined only by experiment. Considerable literature exists from fission reactor experience and changes in material properties induced by displacement radiation damage need to be incorporated into the first wall design. Neutron transmutation reactions are expected to be considerably different from fusion compared to fission neutrons and in particular, helium generation rates from n,α reactions can be very high in many materials in fusion reactor first wall regions. The changes expected in materials properties are largely unknown but will also have to be factored into the design. An optimum design would be one where lifetime limits from radiation damage and erosion, for example, and other limiting parameters all coincide. Significant economic penalty can be imposed on fusion reactors from radiation damage and much further work is needed to understand and limit the effects.

The production of radioactive isotopes by fusion neutron transmutation is another important consideration for first walls especially since here is where the highest neutron flux exists. Quantitative estimates of isotopic concentrations, radiation source terms, local energy generation, and radiation fields around the reactor can all be made reliably. We have selected a general fusion reactor first wall and blanket region design and made the neutron calculations for several of the phenomena of interest.[11,12] The design model consisted of a one-dimensional cylindrical geometry with an inner 0.01 m thick first wall; a 0.5 m thick blanket with 20% structure and 80% Li_2O breeding material; and an outer 0.5 m thick graphite reflector. Several different materials for the first wall and blanket structure were considered.

The decay heat effects are summarized in Fig. 5 where the temperature rise of a perfectly insulated first wall (adiabatic) is

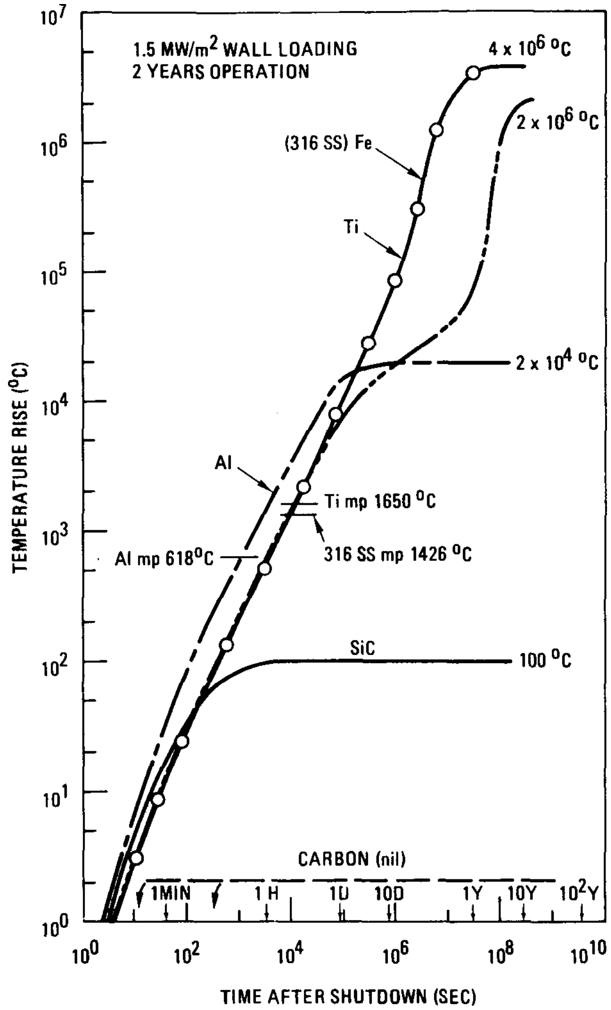


Fig. 5. Decay heat effects expressed as adiabatic temperature rise as a function of time after shutdown for several materials

shown as a function of time after shutdown. The asymptotic temperatures are calculated from the total energy available from decay and are significant for all materials except carbon and silicon carbide. Melting points of 316 SS, aluminum and titanium are also indicated and as can be seem are reached in relatively short times. Prevention of melting clearly requires incorporation of a reliable cooling system for afterheat removal.

Typical times for melting of the first wall are shown in Table 4 along with some selected operating conditions. Again, carbon and SiC never have a decay heat problem, while the metal materials would require initation of suitable shutdown cooling to prevent melting within times ranging from 17 minutes for aluminum to 11 hours for vanadium. The second row shows the time after shutdown at which the

TABLE 4

POST SHUTDOWN HEATING CHARACTERISTICS
($1.5\ MW/m^2$ WALL LOADING; 2 YEARS OPERATION)

	FIRST WALL MATERIAL					
	CARBON	SiC	Al-ALLOY	316SS	Ti-ALLOY	V-ALLOY
ADIABATIC MELTDOWN TIME	∞	∞	17 MIN	2 HOURS	3 HOURS	11 HOURS
POST SHUTDOWN COOLING CUTOFF TIME	0	0	7 DAYS	30 YEARS	1 YEAR	1 DAY
AFTERHEAT AT SHUTDOWN (W/cm^3)	NIL	0.9	1.1	0.6	0.4	0.2
MELTING POINT (°C)	3320 (SUBLIMES)	2600 (DECOMPOSES)	616	1426	1649	1900
OPERATING TEMPERATURE (°C)	1200	1000	150	400	400	400

energy available from the decay of all remaining isotopes is not sufficient to raise the material from the operating temperature to the melting point. Decay heat cooling must be maintained during this time period to prevent melting damage. This is simply zero time for carbon and SiC, but ranges from 1 day for vanadium up to 30 years for stainless steel. Thus a significant burden in fusion reactor design can be relieved by the judicious selection of first wall materials, as well as blanket structure and other materials.

Because of the diversity and severity of the first wall environmental conditions, it is usually accepted that frequent replacement will be required. Annual replacement frequency may be acceptable though longer times between changes would be desirable. The induced radioactivity in the first wall will determine remote handling requirements and associated downtimes and costs, and long-term storage requirements for radioactive wastes. Calculations using the reactor model above have shown that if 100% pure SiC or carbon were used for the first wall and structure there would be virtually no radioactivity problem and hands-on maintenance would be permitted. Taking iron as a typical representative impurity in these materials we can quantify some radiation field levels as a function of this concentration. A rule of thumb can be derived:

- One atom part per million iron (or equivalent radiation emitter) in a first wall and blanket produces a dose rate of one rem per hour in a plasma chamber.

A dose rate of 4 mrem per hour outside the blanket region of a fusion reactor also results with the model we have assumed above. Using allowable personnel exposures, personnel access times and allowable impurity concentration can be estimated. Full working time in the plasma chamber would be allowed if the impurity level were maintained to 0.01 ppm equivalent iron (10 mrem/hr). This is probably not economically attractive for early fusion reactors. Free access to the outside of the blanket region would be available with up to 2.5 ppm equivalent iron, an achievable value. The dose values for all stainless steel first wall and blanket structure may be estimated at approximately 10^6 rem/hr in the plasma chamber and 4000 rem/hr outside the blanket. Material transport through wall erosion as discussed above and other processes will disperse radioactive first wall materials throughout many other parts of a fusion reactor plant. This will produce access problems for maintenance, and a variety of problems from the contamination.

The potential for biological hazards resulting from long-term storage of waste first wall materials is shown in Table 5 (taken from Ref. 12). While the decay heat and radiation fields discussed above are primarily from the short and intermediate half-life isotopes ($\lesssim$10 yr) the storage problems arise from the long half-life isotopes ($\gtrsim$10 yr). Here again the differences between materials are very large, nine orders of magnitude, and problems range from very small to those of the same order as for fission products. In summary, almost all of the potentially large engineering and technological problems associated with radioactive materials in fusion power reactors can be reduced to minor proportions by the judicious choice of materials for the reactor structure. As a corollary, carbon and silicon carbide materials need continuing development for first wall applications to assure that low radioactivity fusion systems will be available.

TABLE 5

BIOLOGICAL HAZARD POTENTIAL[a] AFTER SHUTDOWN IN SiC, C, Al, 316SS, AND Ti-STRUCTURED BLANKETS (ASSUME 1.5 MW/m^2 WALL LOADING FOR TWO YEARS)

TIME AFTER SHUTDOWN	STRUCTURAL MATERIAL				
	SiC	C	Al	316SS	Ti[b]
0	14.5	7.8	34.2	6.52×10^2	2.0×10^2
1 DAY	6.7×10^{-8}	1.9×10^{-8}	7.7	3.88×10^2	2.0×10^2
1 MONTH	1.8×10^{-8}	1.9×10^{-8}	3×10^{-3}	2.66×10^2	1.0×10^2
1 YEAR	1.8×10^{-8}	1.9×10^{-8}	3×10^{-3}	8.33×10^1	5.0
10 YEARS	1.8×10^{-8}	1.9×10^{-8}	3×10^{-3}	7.7	2.0×10^{-3}
100 YEARS	1.8×10^{-8}	1.9×10^{-8}	3×10^{-3}	2.91×10^{-1}	5.0×10^{-4}

(a) IN UNITS OF km^3 OF AIR PER kW(th).

(b) TAKEN FROM THE NUWMAK.

Discussions and Conclusions

The uncertainties in the magnitudes and ability to control the energy partition between plasma radiation and charged particle energy, and in the actual energy spectrum of charged particles on first wall components is a major contributor to uncertainties in projecting fusion reactor performance. A recent proposal by Ohyabu[13] for an expanded boundry divertor for control of the boundry conditions at the first wall may provide a significant improvement. In this concept, the magnetic field divertor directs the charged particles in the boundry region to a chamber immediately adjacent to the plasma. Some of the charged particle energy is then transferrred to radiation through interaction with a low pressure gas, and thus could be reduced to below the sputtering threshold before impinging on the walls. This would then reduce heat loads and erosion of all first wall components.

Absorption of energy from major plasma disruptions is another serious problem for power reactors. An "ergodic magnetic limiter" has been proposed by Ohkawa[14] which would keep the magnetic "surface where the safety factor is equal to 2 outside the plasma" and thus contribute to avoiding major current disruptions in tokamaks. This "ergodic" limiter would also provide a cold plasma edge transition region between the plasma and wall which would help disperse energy uniformly on the wall and reduce erosion.

The design of first walls, and particularly limiters for the next generation fusion devices is a particularly difficult problem because of localized energy deposition from normal operation and the necessity to provide for all the disruptive conditions over many cycles of operation. In efforts to maximize the useful plasma volume, the volume and area for limiters and the plasma wall transition region are kept small. These also tend to produce high heat fluxes over small areas. Many disruptions are also required in order to define limits for stable plasma operation. Similar operating scenarios would be expected in the first ignited plasma and power producing devices such as the Engineering Test Facility. Time consuming tasks of changing first wall components because of damage will be more common in the experimental devices than in projected fusion power reactors. Exploration of the adverse operating conditions to determine where sufficiently stable regions lie for successful power reactors will be a necessary part of the experimental program. It is to be expected that that understanding of the particularly severe operating regimes can be put on a level where occurances are limited to operating errors, equipment malfunctions, or other definable accidental events rather than simply random occurances. If this can be achieved, the design of first walls for power reactors should be an easier task than for the experimental power devices.

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