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ABSTRACT

Plasma interactive components (PICs), including the first wall, limiter blades, divertor collector plates, halo scrapers, and RF launchers, are exposed to high particle fluxes that can result in high sputtering erosion rates and high heat fluxes. In addition, the materials in reactors are exposed to high neutron fluxes which will degrade the bulk properties. This severe environment will limit the materials and designs which can be used in fusion devices. In order to provide a reasonable degree of confidence that plasma interactive components will operate successfully, a comprehensive development program is needed.

Materials reasearch and development plays a key role in the successful development of PICs. The range of operating conditions along with a summary of the major issues for materials development is described. The areas covered include plasma/materials interactions, erosion/redeposition, baseline materials properties, fabrication, and irradiation damage effects. Candidate materials and materials development needs in the near term and long term are identified.

Introduction

Plasma Interactive Components (PICs) include the first wall, impurity control structures, direct convertors, halo scrapers, RF antennas, and other structures which are directly exposed to the fusion plasma. PICs are expected to experience extremely harsh environments. They must not only withstand high heat and particle fluxes from the plasma, but they must also withstand 14 MeV neutron damage in fusion reactors. For commercial applications, useful heat must be extracted from PICs for economic operation. The severe operating conditions will necessitate development of special materials. The requirements for these materials are quite varied since there are a number of different components, confinement concepts, and stages in development which need to be considered.

PIC development is complicated by the large number of disciplines that are involved in resolving key issues and by the numerous links to other parts of the fusion program. Disciplines included are plasma physics, surface physics, solid state physics, metallurgy, ceramics, thermal-hydraulics, chemistry, and electromagnetics. PICs have a major impact on plasma performance, and they are part of both plasma technology and nuclear technology development. They have an impact upon tritium systems, magnet systems, vacuum systems, blanket systems, and remote maintenance. Materials development for PICs is a crucial part of the overall development process, since operating requirements are likely to push the materials to the limit of their capability.

Previous design studies and data base assessments have identified operating requirements candidate materials, and major development issues. [1-8] Recently, the Technical Planning Activity (TPA) has outlined the major programs and development time frame for PICs. [9] This paper will briefly review the previous work and then go on to detail the development requirements for PIC materials.

Operating Environment

The possible operating range for PICs is shown in Table 1. This table is based largely upon the design studies performed for impurity control components [1-4]. The environment for other PICs is more poorly defined, but it is expected to be similar to that for impurity control components. In the near term, the environment is dominated by high particle and heat fluxes. The length of the burn pulse is short, and active cooling of PICs may not be required. In the long term, PICs will still be subjected to high particle and heat fluxes, but in addition, they will experience high neutron fluxes and fluences. The burn cycle length will be long (>100s), and thus, active cooling will be required.

The first wall of a fusion device represents a special class of PIC in that the operating conditions will be significantly different from other PICs. As shown in Table 2, the first wall is expected to see a reduced heat and particle flux. At the low heat flux level, nuclear heating will become an important factor in determining the temperature profiles. Since the first wall is usually incorporated into the blanket, it will be expected to withstand very high levels of radiation damage.

PICs must also be capable of withstanding off-normal events. The most severe events that are anticipated are plasma disruptions, which are observed in tokamaks. The disruption conditions are not well characterized, but estimates have been made for several reactor design studies.[3-4] Disruptions occur over short time periods, and they will result in vaporization and melting of the exposed surfaces. The time scale for the plasma quench phase of the disruption is estimated to be 1-3 ms, and the time scale for the current quench phase is estimated to be 10 - 20 ms. The energy deposited on the surface can range from 50 - 1000 J/cm^2 Large electromagnetic forces within the PIC structures will also occur during disruptions. These forces are the result of interaction of eddy currents, which are induced in the structure, with the toroidal magnetic field. One of the consequences of the electromagnetic forces could be the movement and loss of the melt layer. Over the life of a fusion device, it could experience 10^3 - 10^5 disruptions. In the near term, disruptions are believed to be the primary cause of surface erosion and probably represent the most important life limiting phenomenon.

Issues and Data Needs

A number of materials related issues have been identified (7,8,10). This section summarizes those issues and identifies data needs for each issue. The issues can be divided into surface related issues and bulk materials issues. The issues and data needs are summarized in Table 3.

Recycling

Recycling refers to the processes by which plasma ions leave the discharge, impinge on a material's surface, become neutralized, and reenter the plasma. To the extent that the plasma ions recycle at the wall or limiter, less fueling is required for operation. It is also true, however, that impurity ions may recycle, thus aggravating the contamination problem. Also, energetic ions may result in a recycling fraction greater that unity. This would make density control difficult, and might also change the deuterium-tritium ratio in an uncontrollable way. Not much is known about controlling recycling at the walls. Past experiments have used titanium and chromium gettering to effect such control; however, these techniques are not applicable to either a near-term or a long-term burning fusion device.

When neutrals that are formed on the neutralizer plates are reionized and reneutralized, strong recycling can occur. This can result in an increase of the energy lost by radiation, which reduces the heat load on the neutralizer plate.

The data needs for the recycling issue include; 1) reflection coefficients and reflected particle energy and angular distributions at low incident energies (1 - 100 eV) on single and multielemental surfaces, 2) hydrogen trapping, diffusion, and re-emission rates from surfaces, and 3) sputtering yields, distributions, and physical properties of original and redeposited surfaces for elemental and compound material. In addition, some materials, such as graphite, may chemically erode, and thus there is a need to study chemical erosion and recycling behavior.

Surface Conditioning and Cleaning

Surface conditioning is necessary to minimize impurity influx from thermal and particle-induced outgassing and to stabilize the hydrogen recycling properties of the surface. In addition, conditioning minimizes the tendency for unipolar arc formation. Conditioning is also required for neutral beam and rf heating systems to minimize high-voltage breakdown.

The conditioning of PICs involves careful pretreatment (cleaning and vacuum baking) of the material to ensure good vacuum qualities (i.e., low outgassing surfaces, bulk material free of large voids, defects, and cracks that can serve as leak paths). In addition, *in situ* conditioning involving baking and extensive interaction with hydrogen plasmas or atomic hydrogen is necessary to minimize plasma-wall interactions. Successful wall conditioning has been done when low-Z impurity introduction from first wall and limiter surfaces is negligible, the hydrogen recycling properties are well characterized and static, and the tendency of unipolar arc formation is minimal.

In contrast to the conditioning of stainless steel vacuum vessel surfaces, the conditioning of other PIC surfaces remains an open issue.

The data needs for conditioning are in optimizing the conditions and processes for plasma conditioning surfaces in the next generation devices. The chemical and structural changes that occur at the surface (or near surface) during conditioning needs to be quantified. For reactor applications, the need for in situ surface conditioning will diminish, as the high heat loads and much higher duty cycle will accelerate the conditioning process.

Erosion/Redeposition

Energetic plasma edge particles will strike the surface of plasma interactive components and cause sputtering erosion. It is expected that the sputtered particles will enter the scrape-off region and possibly the main plasma, will be recycled, and eventually will be redeposited on other exposed surfaces. Calculations predict that the redeposition process is important in reducing the impurity level in the plasma and for extending the erosion lifetime of plasma interactive components. At present, there is little data base for erosion/redepostion effects because of the short pulses and low availability of present experimental devices. In addition, the plasma scrape-off conditions found now are quite different from those expected in an ignition device or a reactor.

Redeposited materials may exhibit properties which are inferior from those of the base materials. The actual properties are unknown because materials of sufficient thickness have not yet been produced.

The plasma edge temperature is a key parameter which will affect both the materials selection and component lifetime. At moderate temperatures ($\gtrsim$ 100 eV) it will be necessary to use low-Z materials such as graphite or beryllium in order to avoid self-sputtering resulting from particle recycling and to minimize the effective Z of the plasma. Model calculations predict, however, that sputtering erosion may still be excessive at moderate temperatures even when redeposition is taken into account. At low edge temperatures ($\lesssim$ 50 eV), on the other hand, high Z materials such as tungsten or tantalum may be employed because self-sputtering is no longer a concern. Model predictions for low edge temperatures indicate that erosion will be low for high-Z materials and will be largely compensated by redeposition.

Some of the data needs for erosion/redeposition are similar to the recycling data needs, including sputtering yields, distributions, and physical properties of original and redeposited material. Chemical aspects of sputtering erosion are also relevant. Data are needed on the properties of redeposited material. The properties of interest include adhesion strength, chemical composition, morphology and surface topology, and physical properites (e.g., thermal conductivity, electrical resistively, strength, and ductility).

Disruptions

Disruptions can generally be described as a rapid reduction in the plasma current accompanied by the localized deposition of much of the plasma energy on an interior surface. Disruptions are observed in all tokamaks, and the phenomenon is poorly understood. Consequently, elimination of disruptions for future near-term machines cannot be assured, and PICs must be designed to withstand the induced forces and high heat fluxes that accompany these events.

From the point of view of damage to in-vessel components, disruptions can be divided into two phases: the thermal quench phase, which produces localized high heat fluxes, and the current decay phase, which induces large forces on the vacuum vessels and on in-vessel components. In considering the thermal quench in component design for near-term applications, one generally assumes that one-half of the stored plasma energy is deposited on a single component, such as a single limiter module. The time scale estimated for this energy deposition is on the order of 1ms. Further, the energy deposition is observed to be highly localized, and heat fluxes well in excess of 10 kW/cm^2 should be expected in future machines.

Heat fluxes of this magnitude can cause surface vaporizaton and melt-layer formation. The interaction between the vaporized surface material and the incident plasma is not understood. The difficulty of stability analysis of the surface melt layer is compounded by the induced eddy current forces generated during the current decay phase that act on it.

The primary materials data needs are the determination of materials properties of melted and resolidified materials. The properties of interest are the morphology and microstructure along with the physical and mechanical properties of the resolidified and the heat affected material. The effect of disruptions upon heavily irradiated material may be particularly significant because the microstructure and hence the properties will be altered significantly.

Tritium Inventory and Permeation

The repeated exchange of hydrogen isotopes between the plasma and surrounding walls is a dominent factor in plasma refueling in near term devices. In addition, the tritium which is retained and diffuses through the PIC structure will impact the tritium inventory and safety of fusion reactors in the long term. Tritium inventory and permeation is both a surface and bulk materials issue.

Tritium permeation through PIC materials is a potentially serious problem area for advanced D-T reactors operating at elevated temperatures. High concentrations of tritium in the near surface region can occur by implantation of the charge exchange neutral flux combined with a relatively slow recombination of these atoms into molecules at the plasma/first wall interface. Because of this large concentration of mobile tritium near the inner (plasma) wall surface, a concentration gradient is established, causing tritium to diffuse into the bulk and eventually to the outer wall surface where it can enter the first wall coolant. Calculations have shown that the choice of inappropriate materials (e.g. V for the MARS direct convertor) could lead to tritium permeation as large as 10^8Ci/day.

Two types of experimental data for high heat flux materials is needed. First, for many materials such as TiC, graphite, etc., the hydrogen solubility and diffusivity is not well known. Knowledge of these properties makes it possible to obtain a preliminary estimate of tritium permeation. Second, for those materials of serious interest, a direct measurement of recombination constant is needed. Since this constant depends strongly on both temperature and surface conditions, a measurement with conditions appropriate for machine operation must be obtained.

Thermal Hydraulics/Heat Transfer

PIC's must be capable of adequate removal of heat in the near turn and must also provide high temperature heat removal for economic operation in the long term.

Due to its excellent heat transfer capabilities and data base, water is the preferred near-term collant. Since useful heat removal is not a requirement, low temperature (<100° C) water will be used. Some of the major concerns in the area of thermal hydraulics are heat transfer limits (normal and augmented); flow distribution and stability; channel erosion; and heat source profile. Heat transfer limits arise from a transition to a less efficient heat transfer mechanism (e.g., critical heat flux); limits on increasing flow velocity (e.g., pressure drop, choked flow, channel erosion, flow vibrations); or temperature limits (e.g., coolant boiling, thermal decomposition, solidification, energy recovery efficiency, structural mechanical strength, chemical compatibility). While considerable experience exists in these areas from other technologies, the data usually apply to parameter ranges and geometries that are not directly applicable to fusion designs. For this reason, analysis and testing continue to be necessary to qualify in-vessel components.

In addition to water, long-term options include other coolants such as helium, liquid metals, organics or molten salts for safety, efficiency, or design simplicity reasons. This choice is closely related to the primary blanket coolant choice.

Adequate characterization of the heat source profile is a general issue since there is usually little tolerance for unexpected local hot spots, but such characterization is fusion device specific.

The primary uncertainties in heat transfer limits are critical heat flux (water, organics, molten salts), pressure drop (liquid metals) and flow stability (all). For heat fluxes up to about 4 MW/m^2, there is reasonable confidence for design predictions, although one-sided CHF measurements for liquid coolants (water) at long L/D are desirable. However, liquid metals require substantial effort to reach even these heat fluxes because of uncertainties in MHD effects under realistic geometries. For Heat fluxes above 5 MW/m^2, it is necessary to know the relevant CHF limits. If heat transfer augmentation is used, it will also be necessary to determine the corresponding heat transfer and pressure drop correlations.

Specific materials data needs include determination of heat transfer coefficients across boundaries and the determination of thermophysical properties for the candidate materials. Additional data is required on the erosion and corrosion of flow channels. This information is needed to set limits on coolant flow rates and temperatures.

Thermomechanical effects

Thermal stresses are caused when temperature changes induce thermal expansion in a constrained material. These stresses can be very large in PICs since they are exposed to high surface heat fluxes and large temperature gradients. Thermal fatigue becomes a concern when the heat flux is cycled, as is the case of current and near-term pulsed tokamak fusion devices. Damage caused by thermal fatigue occurs in two stages: crack initiation and crack growth.

For the next generation of fusion devices it will be necessary to bond armor tiles to the heat sink structure of actively (or, in near-term experiments, inertially) cooled PICs. Two examples are graphite bonded to molybdenum cooling tubes and beryllium tiles bonded to a copper heat sink. The long-term structural integrity of the bond is a critical issue for PICs since debonding will cause rapid overheating of the armor material and eventual failure of the system.

Thermal fatigue and bond integrity are two problem areas that are of long-range concern. In plasma interactive components, the growth of thermal fatigue cracks can cause: 1) debonding of armor tiles, 2) coolant leakage, or 3) catastrophic fracture of pressurized components. Prevention of each of the three failure modes will require extensive testing and improved models for failure analysis.

The important basic materials properties are fatigue crack growth rate and fracture toughness for the appropriate environment. The interaction of fatigue with creep damage will become important when pulse lengths become significantly long. For stainless steel, the materials data base is considered to be adequate for design purposes. However, for materials relevant to plasma interactive components, such as beryllium, molybdenum and copper alloys, the data base for thermal fatigue is inadequate. Even if the basic properties are well known, thermal fatigue is such a complex phenomenon that accurate predictions are unlikely. This places a greater reliance on full scale testing to qualify these components. As the availability, number of cycles, heat fluxes, neutron damage, and operating temperatures increase for long-term applications, thermal fatigue will clearly become a critical issue that may play an important role in deciding between pulsed or steady-state fusion devices.

Fabrication

Fabrication of PICs involves the bonding of a plasma-side material to a structural heat sink. Both the plasma side and heat sink may consist of special materials for which there is little or no fabrication data base. Fabrication of the base materials and of the assembled PICs needs to be demonstrated. Of particular interest is the interface bond; in many cases there is a large mismatch in the physical properties of the materials which make attachment especially difficult. The successful fabrication of materials and bonding over lengths approaching 1 m presents a significant issue for fusion.

Materials data needs involve the determination of fabrication methods which optimize materials properties. Since fabrication methods can have a significant impact on bulk properties, it is desirable to use materials which have been fabricated by these methods as the source of specimens for other areas of material testing.

Irradiation Response

Neutron radiation damage will affect almost all of the bulk properties, and therefore it is an issue which affects all other bulk materials issues. Since near term devices will experience little or no 14 MeV neutrons, irradiation response is primarily a long term issue. The need for irradiation data is immediate, however, due to the long lead times requried to accumulate high fluence data. The effects of radiation can be divided into four categories (1) effects on thermophysical properties, (2) effects on mechanical properties, (3) effects on dimensional stability, and (4) activation.

Thermophysical property changes are observed to the greatest degree in non-metals. The properties most severely affected are thermal conductivity and electrical conductivity. Reductions in thermal conductivity will limit the capability of materials to accommodate high heat fluxes. Changes in electrical properties will affect plasma heating components that must use insulator materials.

Radiation damage will degrade the mechanical properties through changes in tensile strength and ductility. The change in tensile strength will depend upon the initial microstructure and service temperature. Embrittlement may occur by changes in the ductile to brittle transition temperature, radiation hardening or high temperature helium embrittlement. The effects of radiation on mechanical properties are most important for the structural materials.

Radiation will affect dimensional stability through radiation enhanced creep and swelling. Swelling is highly sensitive to alloy composition, gas content, and dislocation and precipitate microstructure. For PICs where different materials are bonded to each other, differential swelling could be very important. At temperatures <0.4 T_m the phenomenon of irradiation creep becomes important and in some situations can become the major source of dimensional changes. It also plays an important role in the relief of secondary stresses. The dominant irradiation creep mechanisms involve the stress-oriented nucleation of interstitial loops or the climb-controlled glide of dislocations. Irradiation creep is strongly coupled to void swelling and is therefore, sensitive to alloy composition and microstructure. Enhanced creep at low temperatures will limit the allowable stresses during normal operation.

Activation relates primarily to the safe disposal and recycling of materials following the end of life for PICs. Since most of the important materials properties related to activation are determined by materials selection, it provides the incentive for development of special alloy compositions with lower activation advantages. Radioisotopes with half-lives longer than five years are of concern in determining the long-term waste disposal of an irradiated reactor component. Achieving only waste that meets "Class C" or better classification under current regulations mainly requires control of Cu, Mo, N, Nb and Ni.

Candidate Materials

The severe operating requirements for PICs limit the choice of candidate materials. Previous design studies have identified the different classes of materials [1-5], and these materials, along with key advantages and disadvantages are shown in Table 4. The plasma side materials include graphite, beryllium, silicon-carbide, beryllium oxide, tungsten, and tantalum. These materials all have high thermal conductivities in order to accommodate high heat fluxes. The structural materials include stainless steels, copper alloys, and refractory alloys of vanadium, niobium, and molybdenum. No materials stand out as being the best choices for various applications. Therefore, the specific selection of materials will depend upon the particular application and operating conditions.

In general, the characterization of the materials shown in Table 2 is poor, and hence there are major data needs. The data needs for plasma side materials include both surface and bulk properties. First, baseline property characterization is needed for all candidate materials. In the case of graphite, it is important to identify a reference graphite, since the properties vary considerably depending upon the type of graphite.

There may be a need to determine the baseline properties of candidate materials from different fabrication procedures. The surface related properties include recycling and sputtering (physical and chemical). The bulk properties of interest are hydrogen trapping, retention and permeation and in the long term, the effects of neutron radiation damage.

Baseline property data is also needed for the structural materials. In the near term, the materials of greatest interest are copper alloys. For high temperature operation, however, copper alloys will not be adequate, and so refractory metal alloys may be required. Other properties of interest include erosion/corrosion effects by coolants, long term activation, and the effects of radiation damage on mechanical properties and dimensional stability.

Schedule for Development

The timetable for development of PICs will be set in large part by the projected construction schedule for the future fusion test devices. The two largest devices planned between now and the year 2000 are the short pulse ignition device and the long burn device [9]. These devices represent the principal test beds for burning plasmas, and therefore provide the most appropriate test environment for PICs. The test schedule for materials development, outlined below, therefore assumes that PIC development will be tied closely to these devices. Of course, there are other long term issues, such as neutron irradiation effects and useful heat removal, that apply to commercial devices and which must be addressed in other facilities. The timetable for construction and operation of the burning plasma devices is taken from the Technical Planning Activity report [9].

The short pulse ignition device is scheduled to begin operation in 1992. The materials development work must therefore be completed by about 1990 in order to design and construct the PICs prior to 1992. The materials related programs involve the choice of the plasma side materials, the choice of heat sink materials, the selection of the attachment method for the plasma side materials to the heat sink, the choice between inertially cooled and actively cooled components, and the selection of optimum fabrication methods.

The leading candidate for plasma side materials are graphite and beryllium. If a divertor is used for impurity control, then tungsten or tantalum would also be candidate materials. A large data base exists on the use of graphite in plasma devices, but there are several surface related properties, described in various sections, which need to be investigated. There is much less experience with beryllium, and therefore the development requirements are greater. In addition to studying surface related properties, baseline bulk properties must be established, and fabrication methods must be developed. This is also the case with tungsten and tantalum where there is limited experience. The choice of heat sink materials is between stainless steels and copper alloys. Copper alloys may be required in a compact ignition device to accommodate the higher heat fluxes. If beryllium is used, it will need to be metallurgically bonded to the heat sink in order to maintain the surface temperatures at an acceptable level. Thus bonding develpment would be required.

The long pulse device is scheduled to begin operation in 1998, so that materials development for PICs should be completed by about 1996. The surface materials of interest are the same as those used in the ignition device, and therefore operating experience from the ignition device will provide valuable information for development. In contrast with the ignition device, PICs will definitely need to be actively cooled and they will experience modest amounts of radiation damage (10-20 dpa). Since many materials, particularly non-metals, can be seriously affected by low to moderate levels of radiation damage, there is a need to determine neutron effects in candidate materials. Since it is likely that the PIC materials will operate at low to moderate temperatures ($T < 500° C$), it is important that irradiation tests be conducted at the appropriate temperatures. Neutron damage characterization is also needed for heat sink materials and bonded structures.

Erosion/redeposition will be a significant issue for the long pulse device. This issue combines plasma physics, surface physics, and bulk materials characterization. It is important that multiple effects testing on erosion/redeposition be conducted in order to characterize the phenomena in the long pulse device.

Beyond the long pulse device, there is a need to examine the effects of high neutron fluences (50 - 100 dpa) on PIC materials. There is also a need to extract high temperature heat for energy conversion. This means that the materials must be capable of operating at higher temperatures than in the long pulse device. It is presently believed that refractory metal alloys can provide the advantages of elevated temperature operation and increased irradiation of damage resistence over copper alloys. Thus, the development and characterization of refractory metal alloys is needed in the long term. The effects of neutron damage will limit the selection of plasma side materials. It is not clear which, if any, of the present candidates are capable of withstanding high fluence levels, and a major development program is needed.

Conclusions

The development of materials for PICs represents a near term issue for fusion with the present schedule for the short pulse ignition device. Most of the candidate materials are poorly characterized, and hence expansion of the present programs will likely be needed. The areas of greatest interest are the surface related issues that have a direct impact on plasma performance.

Many of the surface related issues are also important for the long term. However, because of the different operating conditions and requirements the PIC materials may be different from those used in the short pulse ignition device. Due to the limited data base, the bulk properties of both the plsama side and structural materials need to be thoroughly characterized. In the long term, irradiation damage effects become important, and there is a need to characterize these effects for PIC materials to moderate fluences. For reactor applications high fluence effects need to be examined, and the limits for useful heat removal need to be determined.

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The material presented in this paper represents a summary of the work of many people involved in identifying the issues and development needs for Plasma Interactive Components. In particular, the author would like to acknowledge the contributions of the members of the High Heat Flux Materials and Component Task Group, the Task Group on Plasma/Materials Interaction, and the Technical Planning Activity. This work is supported by the U.S. Department of Energy.

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List of Tables

Table 1 - PIC Operating Parameters

Parameter	Near Term	Long Term
Heat Flux	2 - 7 MW/m^2	1 - 10 MW/m^2
Neutron Flux	2 - 5 MW/m^2	2 - 10 MW/m^2
Neutron Fluence	< 0.1 dpa	20 - 100 dpa
Burn Time	5 s	>100 s
Edge Temperature	10 - 100 eV	10 - 200 eV
Coolant	None	Water, He
	Water	Liquid Metals
Particle Flux	10^{21} - 10^{22} m^{-2} s^{-1}	10^{21} - 10^{22} m^{-2} s^{-1}
Surface Temperature	800 - 1800° C	$\lesssim$ 1000° C
Heat Sink Temperature	$\lesssim$ 300° C	$\lesssim$ 750° C
Number of Cycles	3000 Full power 10^5 Total	10^3 - 10^6
Configuration	Tiles mechanically or metallurgically attached to heat sink	Coating/Cladding metallurgically bonded to actively cooled heat sink

Table 2 - First Wall Operating Parameters

Parameter	Near Term	Long Term
Heat Flux	0.2 - 0.6 MW/m^2	0.1 - 1.0 MW/m^2
Neutron Flux	< 0.1 dpa	100 - 200 dpa
Coolant	None, Water	Water He, Liquid Metals
Surface Temperature	$\lesssim$ 300° C	$\lesssim$ 750° C
Configuration	Bare wall or tiles mechanically attached	Actively cooled bare metal wall

Table 3 - Materials Related Issues for Plasma Interactive Components

ISSUE	TIME FRAME	SURFACE/BULK	ITEMS TO BE RESOLVED	MATERIAL DATA NEEDS
Recycling	Near term/ Long term	Surface	Reflection of energetic hydrogen isotopes Photon, electron and ion desorption Hydrogen trapping, diffusion, and molecular recombination	Reflection coefficients, particle energy and angular distributions at energies of 0-100ev Hydrogen isotope trapping and re-emission rates from surfaces Sputtering yields, distributions, and physical properties of original and redeposited material
Surface conditioning and cleaning	Near term	Surface	Minimize impurity influx from thermal and particle-induced outgassing Determine pre-treatment methods	Determination of chemical and structural changes during conditioning process
Erosion/Redeposition	Near term/ Long term	Surface	Impact of erosion/redeposition on plasma impurity levels Impact of erosion/redeposition on net erosion rates	Sputtering yields, distributions, and physical properties of original and redeposited materials Chemical effects on sputtering
Disruptions	Near term/ Long term	Surface	Establish Disruption Conditions Determine levels of erosion and damage during disruptions	Properties of resolidified materials Properties of heat affected structures
Tritium inventory and permeation	Near term/ Long term	Surface/Bulk	Buildup of Hydrogen isotopes in near surface and bulk of PICs Permeation rates into coolant	Surface recombination rates Influence of coatings on permeation Neutron effects on tritium trapping Near surface trapping of tritium Hydrogen solubility and diffusity
Thermal Hydraulics and heat transfer	Near term/ Long term	Bulk	Heat flux limits for PICs Temperature limits for PICs	Thermophysical properties of PIC materials Erosion/corrosion rates of structural materials by coolants
Thermo-mechanical effects	Near term/ Long term	Bulk	Determine thermal stress and fatigue limits for PICs	Thermophysical properites of PIC materials Mechanical properties (fatigue-crack growth) Properties of bonds
Fabrication	Near term/ Long term	Bulk	Bonding of dissimilar materials Fabrication methods for large (> $1m^2$) structures Fabrication methods for optimize microstructures	Bond properties and optimization Properties of as fabricated structures
Irradiation response	Long term	Bulk	Irradiation damage limits for PIC materials	Determination of effects of neutron irradiation on thermophysical properties mechanical properties dimensional stability activation

TABLE 4 - CANDIDATE MATERIALS FOR PICs

MATERIAL	COMPONENT	ADVANTAGES	DISADVANTAGES
Graphite	Limiters First wall armor	Availability Experience in present devices Low-Z Low activation High T capability High thermal shock resistance	Limited radiation lifetime Hydrogen retention Chemical sputtering
Beryllium	Limiters Halo scrapers	Low-Z Low activation Low tritium permeation	Limited radiation lifetime Safety Concerns Possible melting during disruptions
BeO	Limiters RF windows	Low-Z Low activation Favorable electrical properties	Limited radiation lifetime Safety concerns Possible electrical and thermal property changes during irradiation
Tungsten	Divertors	High-Z (low edge T) High Temperature capability Low tritium permeation	Limited radiation lifetime Difficult fabrication
Tantalum	Divertors Heat sinks	High-Z (low edge T) High temperature capability Liquid metal compatibility	High tritium permeation Incompatible with He coolant
Molybdenum	Halo scrapers Direct convertors	High temperature capability	High activation Limited irradiation lifetime Difficult fabrication
SiC	Limiters First wall armor	Availability Low-Z Low activation High temperature capability	
Stainless Steels	First wall Structural base for mechanically attached limiter	Availability Large Data Base Good fabricability	High activation Poor thermal properties
Copper Alloys	First wall (compact devices) Heat sinks Plasma side (Cu-C)	Availability Good thermal properties Good Fabricability	High activation Incompatible with liquid metals Limited temperature capability
Vanadium Alloys	First wall Heat sinks	Low activation Potential for high radiation resistance Elevated temperature capability Compatible with liquid metals	Limited experience Incompatible with He Coolants Limited thermal properties
Niobium Alloys	Heat sinks	Elevated temperature capability Compatible with liquid metals	High activation
Electrical Insulators (Al_2O_3, MgO, $MgAl_2O_4$)	Plasma heating components	High electrical resistance	Limited irradiation lifetime