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15.7 ITER and beyond
(Session Organizers: M. Seki, R. Matera, F. Tavassoli, J. Davis and D. Smith)

ITER and beyond

Abstract

In the beginning of the session of 'ITER and beyond', a keynote presentation was given by Dr Seki overviewing materials used in ITER (316SS, Cu-alloy, Be, W, CFC, Inconel, Insulators, Cryogenic materials, etc.) together with brief introduction to ITER structural design criteria and fabrication technologies. The overview was followed by two presentations concerning detailed fabrication technologies, inspection and damage detection by Dr Davis, and applicability of the present achievements in materials for ITER to DEMO by Dr Matera. The session was mostly devoted to discuss: (1) Are we confident of the materials selected in ITER?, (2) Can we assure reliable performance of ITER? and (3) Can we expect a bright future for fusion from the viewpoint of materials?

1. Summary of the presentations by M. Seki, R. Matera and J. Davis

1.1. Review of materials used in ITER

The cross-section of the ITER and the main structural components are shown in Fig. 1 together with the list of materials used in these components. Table 1 summarizes the working and environmental conditions of the materials used in ITER.

In the divertor, to withstand high particle and heat fluxes, carbon-fiber-reinforced carbon composites (CFC) and tungsten are selected for the plasma facing material (PFM) and copper alloys for the heat sink and cooling tube materials. The main structure is made of 316SS. The divertor is often referred to as a high-heat flux component. The heat flux is very high, as high as 5 MW/m^2 for steady state and 20 MW/m^2 for 10 s transients. These high-heat fluxes force us to use copper alloys for heat sinks and cooling tubes. The combination of PFM and copper heat sink is selected primarily due to their high-heat flux capability and well-established compatibility with plasma. The PFM is either brazed or active-metal-casted to the copper alloys. Developments of bonding technologies are, therefore, crucial to assure the expected performance of the components in conjunction with improvement of characteristics of each material.

In the blanket/first wall, the preferred PFM is beryllium, which is bonded to the copper heat sink by hot isostatic pressing (HIP). The heat flux expected on the first wall is 0.5 MW/m^2, and thus the use of copper alloys for heat sink material is unavoidable.

The vacuum vessel (VV), which serves as the first confinement barrier for tritium, is made of 316SS. The VV is a double-skinned structure with ribs in between. The space between the inner and outer skins is filled with shield materials and cooled by flowing water at a pressure of 2 MPa. One of the technical issues of manufacturing the VV is welding with minimizing overall deformation within a few mm.

The cryogenic stainless steels and 316SS are used for the superconducting magnet (SCM) structures. Incoloy 908 is used as a coil jacketing material. They work at very high levels of stress as seen in Table 1.

With respect to the support structures, the vertical support of the ITER is made of Inconel 625 and 718, and VV legs are made of 316SS. The toroidal field (TF) coils are supported by the gravity support column of leaf springs made of Inconel 625. The VV is hanged to TF coils by hanger assemblies. This flexible support structure allows to accommodate different thermal expansions due to extremely different operation temperatures.

1.2. Neutron flux and damage of materials

High-energy neutrons produced by DT reactions are one of the key damaging factors to the materials close to the plasma. Fig. 2 shows calculation results of neutron flux as a function of distance measured from the reactor center. The VV and blanket have many ports and

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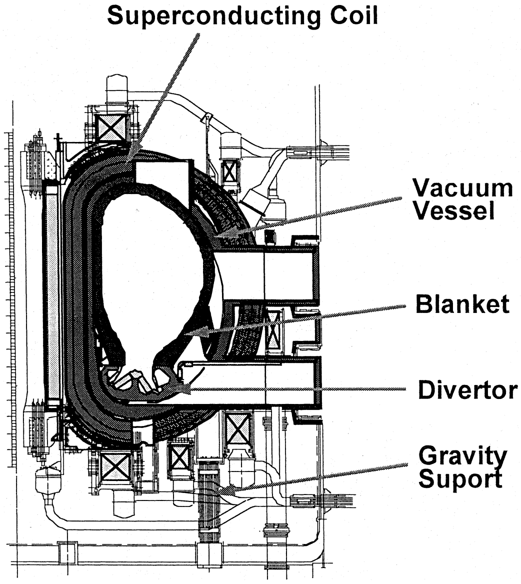

Components	Materials
Divertor	CC/CuCrZr/SS W/CuCrZr/SS Be/CuCrZr/SS
Blanket	CuCrZr/SS Be/CuCrZr/SS
Vacuum Vessel	316LN
SC Coil Jacket SC Coil Case	Incoloy 908 316LN,JJ1,JK2,JN1
Gravity Support VV Leg	Inconel 625 Inconel 718 316LN

Heat sink material:Cu/Cr/Zr or DSCu

Fig. 1. Components and materials in ITER.

openings and thus sophisticated analysis, taking into account the real configuration of shields, is necessary to have accurate results. The result shown here is for the case along the line just above the center ports. The fusion power is 1.5 GW. Both total flux and 14 MeV flux decreases sharply in the blanket and VV regions. Total neutron flux which is about 2×10^{14} n/cm^2/s at the first wall, and about 10^{12} n/cm^2/s at the rear of the blanket, decreased by 2 orders of magnitude in the blanket of 40 cm thickness.

Damage and helium generation of the SS are also calculated and shown in Figs. 3 and 4. The point is that the first wall and the divertor materials are subject to severe neutron damages but the VV is not so serious. The damage to the VV is around 5×10^{-3} dpa and helium production is less than 0.1 appm at a fluence of 1 MWa/m^2. These values suggest that the neutron damage is not life-limiting for the VV. The existing data confirm that the VV can maintain the robustness as the first confinement barrier for tritium for the whole life of ITER.

The materials used in ITER suffer from damages caused by neutron irradiation, stress, corrosion and erosion. Figs. 5 and 6 summarize deterioration of structural materials and functional materials.

1.3. Fabrication technologies, inspection and damage detection

Efforts to assure reliable performance of ITER are made during all aspects of reactor life including design, material and manufacturing process development, component demonstration and testing, quality assurance and inspection, and in-service inspection of components. Technology impacts all aspects of computer-aided design and analysis, development and improvement of materials and manufacturing process, realistic testing of components, inspection and non-destructive testing and remote maintenance and inspection. Technology to improve materials and manufacturing processes in ITER has been developed. This includes use of HIP to bond large areas and use of proven technologies for in-vessel components. Fabrication of large prototype articles such as CS model coils has been made to demonstrate processes and design prior to fabrication of production hardware.

With respect to technology for inspection and non-destructive testing, existing technologies for non-destructive testing developed in aerospace, nuclear and medical industries can be applied to ITER. Advanced technologies such as infrared thermography are also available for fusion. There are extensive experience of remote maintenance and inspection in space and fission industries. Extensive development work is also being performed on ITER.

Need to assure component reliability is not unique to fusion and the ability to perform remote damage detection is being performed in other industries. Thus experiences applicable to ITER exist in other technological areas. Component and machine reliability begins with design, and all four parties in ITER are designing components with reliability and inspectability in mind. Therefore, it can be concluded that reliable performance of ITER can be assured.

Ta ble 1
Working and environmental conditions of the materials used in ITER

Components	Parts	Materials	Temperature (normal/max)	Stress (MPa)	Neutron Flux ($n/cm^2/s$)	Environment coolants	Joining methods
Divertor	Armors	CFC,W	For CFC: 1500°C/1000°C For W: 1000°C/1000°C		0.6 MW/m^2 (peak) CFC: 0.3 dpa	Plasma cooling water 140°C/4 MPa	Brazing HIP Welding
	Heat sinks	DSCu, CuCrZr	350°C/150°C	Pm + S: 300 Pm: 200 (EM) @Wing S: Below 100 @Vertical dump target	14 MeV: 10^9–10^{13} >0.1 MeV: 10^{11}–10^{13} Total: 10^{11}–10^{14}		
	Cooling tubes	DSCu, CuCrZr	350°C/150°C	Coolant pressure: 4			
	Support structures	316LN	250°C/150°C				
First wall/blanket		Be/Cu/SS Joints 316LN	Be:300°C Cu:270°C SS:250°C	Cu: Thermal~190 SS: Thermal~380 Leg(SS): EM~180	14 MeV: 10^{10}–10^{14} >0.1 MeV: 10^{12}–10^{14} Total: 10^{12}–10^{14}	Plasma cooling water 140°C/2 MPa	HIP EB,TIG
Vacuum vessel		316LN-ITER Grade	Max:250°C Nominal: 120°C/BPP 160°C/EPP 200°C/Baking	Pm: 119 Pm + B: 140 Pm + S: 263 (NS-VDE)	Damage: <0.3 dpa He production: <1 appm 14 MeV: 10^5–10^{11} >0.1 MeV: 10^6–10^{12} Total: 10^7–10^{12}	Vacuum cooling water 100°C/2 MPa	TIG MIG EB
Cryostat		304L	Min: 125 K Normal: RT (20°C)	Pm + B: 184	14 MeV: 10^3–10^6> 0.1 MeV: 10^8–10^9 Total: 10^9–10^{10}	In: Vacuum out: Vacuum He–gas cooling	Welding
Back plate		316LN	200–250°C	Thermal~100–150 EM~150–200	14 MeV: 10^{10}–10^{12} >0.1 MeV: 10^{12} Total: 10^{12}		
Superconducting magnets	Superconducting wire	Nb3Sn NbTi Nb3Al	RT/−269°C			Supercritical Helium (SHe)	Diffusion bonding Brazing
	Joint materials	Cu Monel 316L	RT/−269°C			In: SHe Out: Vacuum	Welding HIP
	Jacket material	Incoloy 908 316L JN1HR	RT/−269°C	Pm + B: 520 Pm252		In: SHe out: Vacuum	Welding
	Support structure	316L JJ1, JK2, JN1	RT/−269°C	Pm + B: 750 Pm351		Vacuum	Welding
	Radial plate	316L	RT/−269°C	Pm 667, Pm + B 867		Vacuum	Welding

Table 1 (Continued)

Components	Parts	Materials	Temperature (normal/max)	Stress (MPa)	Neutron Flux ($n/cm^2/s$)	Environment coolants	Joining methods
		JJ1, JK2, JN1					
	TF Coil case	316L	RT/−269°C	Pm 390, Pm + B 490		Vacuum	Welding
		JJ1, JK2, JN1					
	Gravity support	316L	RT/−269°C	Pm 351, Pm + B 648		Vacuum	Welding
		JJ1, JK2, JN1					
	Insulation materials	GFRP	RT/−269°C	Shear stress 21.8, 3×3 mm^2 exceed the allowable on CS		Vacuum	Welding
RF H/CD system	Windows	CVD Diamond	240°C/TBD	TBD	10^{10}–10^{11}	Vacuum, Water: TBD	Brazing (Al or Au)
		(EC)			10^{10}–10^{12}	Vacuum, Water: 100°C, 4 MPa	Brazing (Ag)
		BeO (IC)	240°C/150°C	Thermal: 83			Diffusion bonding
	Anntena	(EC)	240°C/200°C	TBD	10^{14}–10^{15}	Plasma water: 140°C, 4 MPa	HIP
		Cu-Alloy (CuCrZr)					Welding
	(Current strap)	(IC)	240°C/200°C	Pm: 130	10^{14}–10^{15}	Plasma water: 140°C, 4 MPa	Welding
		316LN + CuCrZr		S: 260			
	(Faraday shield)	(IC)	240°C/200°C	Pm: 130	10^{14}–10^{15}	Plasma water: 140°C, 4 MPa	Welding
		CuCrZr + 316LN-tube + Be		S: 90			
	(Casing)	(IC)	240°C/200°C	TBD	10^{14}–10^{15}	Plasma water: 140°C, 4 MPa	Welding
		316LN					
Neutral beam injector	Beamline	Cu	<200°C	TBD	10^{5}–10^{10}	Beam,	Brazing
		316L	20°C			Vacuum, Water	Brazing, Welding
		Al	20°C			Vacuum, Water	Welding
		Steel	20°C			Vacuum Air	Welding
	Ion source	Cu	300°C	TBD	10^{9}–10^{10}	Beam, Vacuum, Water	Brazing
		Ti	40°C			Vacuum,Water	Brazing, Welding
		steel	40°C			Vacuum	Welding
		Al_2O_3	40°C			Vacuum	
		Magnet (SmCo, NdFe)	40°C			Vacuum	

Table 1 (Continued)

Components	Parts	Materials	Temperature (normal/max)	Stress (MPa)	Neutron Flux ($n/cm^2/s$)	Environment coolants	Joining methods
Tritium system	Primary piping	316	RT~373 K	250 kPa (inner pressure)		High-Conc *T*	
	Cryogenic distillation	304L	20 K/RT	150 kPa (inner pressure)		High-Conc *T* /~20 K He LH_2 LT_2/	
	Functional material	Molecular sieve	77 K~RT/573 K	Atmospheric pressure			
						High-Conc *T*	
		Pd alloy	700 K	250 kPa (inner Pressure)		High-Conc *T*	
		ZrCo	RT~400°C/723 K	250 kPa (inner Pressure)		High-Conc *T*	
		Catalyst	RT~500°C	Atmospheric pressure		High-Conc *T*	
		Zirconia	700°C	Atmospheric pressure		High-Conc *T*	
	Secondary glove box	Acrylic resin	RT	50 mm H_2O Negative		Low-Conc *T*	
		Rubber	RT	50 mm H_2O Negative		Low-Conc *T*	
	ADS, VDS, MDS, HDS	Polyimide	RT~100°C	Atmospheric pressure		Low-Conc *T*	
		Molecular Sieve	RT~300°C	Atmospheric pressure		Low-Conc *T*	
		Catalyst	RT~500°C	Atmospheric pressure		Low-Conc *T*	
	WDS	304, Catalyst	RT~473 K	Atmospheric pressure		HTO	
Cooling system		304L	200°C/100°C	Coolant pressure 2			
Diagnostics	MI-Cable	Core:Cu Sheath:SS Insulator: MgO	600°C/ (150°C~300°C)	TBD	Total: 10^{10}~10^{14}	H_2O/He cooling Vacuum/Outside VV	TBD
(1) Magnetic measurement							
	Ceramic Coated Wire	Conductor: Ni or Ti Insulator: Al_2O_3					
(2) Neutron measurement	Precollimator	SS + H_2O	150°C~300°C	TBD	14 MeV: 3×10^9 (On a detector) Total: 10^{10}~10^{17}	H_2O Coolant, vacuum	TBD
	Window Detector	SS Diamond U^{235}	150°C~300°C	TBD		Vacuum/Air	
(3) Optical (LIDAR, reflectometer)	Mirror	TBD (full metal Rh,Al,Cu,Ag,W or Mo)	150°C~300°C	TBD	10^{10}~10^{12}	Vacuum	TBD
	Lens/Window	TBD (Fused silica)	150°C~300°C	TBD	~7×10^9	Vacuum/air	

Table 1 (Continued)

Components	Parts	Materials	Temperature (normal/max)	Stress (MPa)	Neutron Flux ($n/cm^2/s$)	Environment coolants	Joining methods
	Shield	TBD	150°C~300°C			Vacuum	
	Detector	TBD	Room				
	Laser	TBD	Room				
(4) Spectroscopy	Mirror	TBD (Mo,W, Cu or Al)	150°C~300°C	TBD	10^{10}--10^{12}	Vacuum	TBD (Bolt)
	Window	Fused quartz	150°C~300°C	TBD	0.5 MW/m^2	Vacuum/air	TBD
	Fiber	Fused quartz		TBD		Air	
	Detector	TBD					
	Shield	TBD					
(5) Microwave (ECE reflecto-meter)	Mirror	TBD(W)	150°C~300°C	TBD	~100 kW/m^2 (first mirror)		TBD
	Window	Fused quartz		TBD		Vacuum/air	Welding
	Antenna/ transmission	TBD (Cu)					
	Shield	TBD				Vacuum	
(6) Bolometer	Detector	TBD (Au, Ceramics or AlN)	150°C~300°C	TBD	TBD	Vacuum	TBD

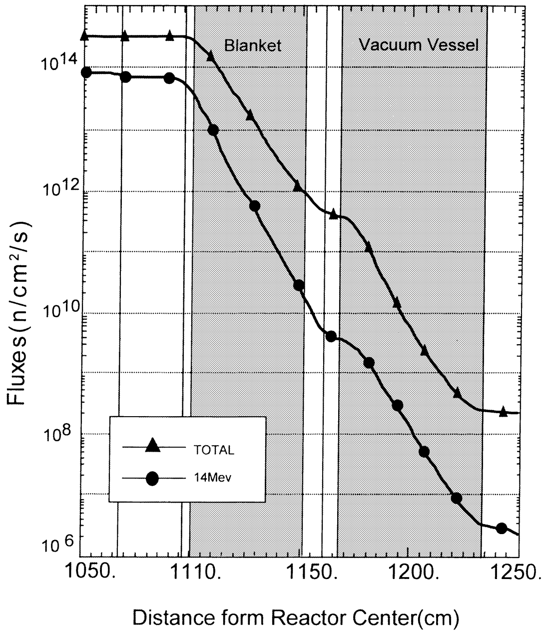

Fig. 2. Calculated neutron fluxes.

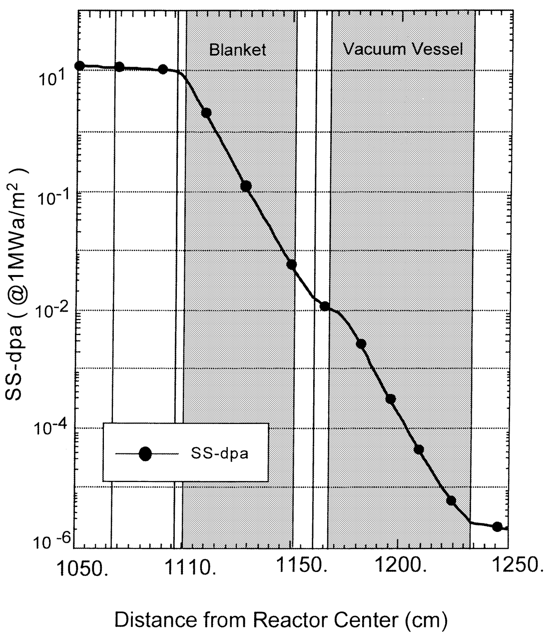

Fig. 3. Calculated damage of SS due to neutrons.

1.4. From ITER to DEMO

Table 2 compares the parameters of the two machines, which are most relevant from the materials point of view. As shown in Table 2, the fusion power, the

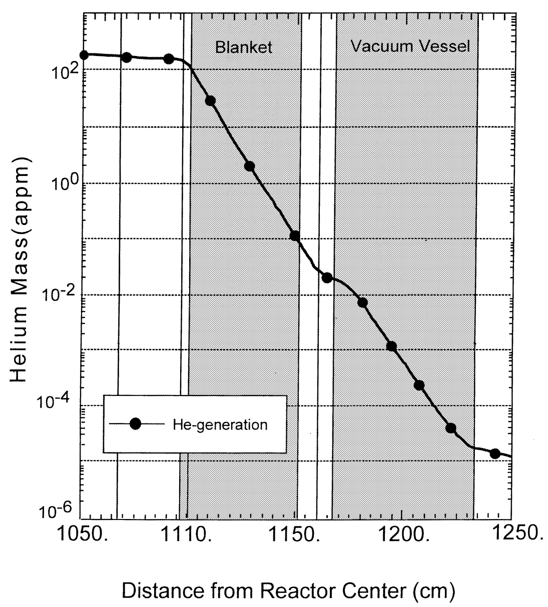

Fig. 4. Calculated helium generation of SS due to neutrons.

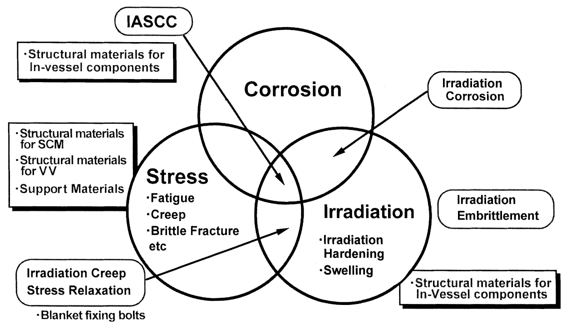

Fig. 5. Deterioration of structural materials.

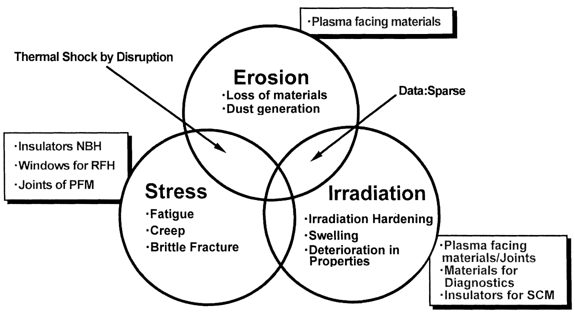

Fig. 6. Deterioration of functional materials.

neutron wall load, the fluence and the neutron damage in the materials surrounding the plasma will be higher in DEMO, while the heat loads on the Plasma Facing Components (PFCs) will be in the range of those we are considering for the ITER PFCs.

An important difference between ITER and DEMO lies in the number of design operating cycles and in the expected number of off-normal events, such as plasma disruptions, VDE and power transient on the divertor plates. My personal feeling is that DEMO will be built only if the progress in plasma physics and engineering allows a steady-state operation of the reactor and if the off-normal events are eliminated or at least if their frequency is reduced to the level of extremely unlikely events. As a consequence, we can expect that the thermal fatigue, thermal shock loads and the electromagnetic stresses due to eddy currents or halo currents on PFCs will be much reduced, if not eliminated, in DEMO in comparison with ITER.

In ITER the choice of PFMs is largely dictated by the plasma–wall interaction phenomena. From Table 3, which is reporting the erosion lifetime evaluation for the Divertor components, we can see that the erosion rates due to off-normal events largely exceed that due to sputtering. In DEMO, it is just the opposite since sputtering should be the main, if not the only contributor to erosion. From the sputtering point of view, W seems to be the preferred option for DEMO but this statement is open to discussion. W as PFM would also eliminate any problem of Tritium co-deposition, which is the limiting factor in using CFC in ITER.

During this conference many presentations dealt with the use of low activation materials, exclusively in connection with the first wall and blanket system. For the DEMO ex-vessel components, the main structural materials will be very similar to the austenitic alloys (Stainless Steels and Ni-based alloys) selected for the ex-vessel structures of ITER. There is a larger scope for developing austenitic low activation materials for the structural materials of the VV, magnet and the cryostat of DEMO than for the savings. In terms of radioactive waste, reduced time for decommissioning and hands-on maintenance outside the VV could be much higher. Moreover, the austenitic low activation materials could be much closer to an industrial development than the low activation materials for the first wall and blanket system. Ferritic steels, vanadium alloys and SiC/SiC composites, the three classes of low activation materials so far developed, have been extensively discussed at this conference.

2. Discussions

2.1. Philipps

With respect to the first wall materials we must not forget to consider the materials from the viewpoint of plasma pollution. At this point, tungsten is a very dan-

Table 2
Comparison between ITER and DEMO parameters

Parameter	ITER	DEMO
Nominal fusion power, GW	1.5	3
Neutron wall load, MW/m^2	1.0	2.1
Thermal load to PFC, MW/m^2	10–20 peak	5–10 peak
Total neutron fluence, MWa/m^2	0.3 BPP > 1.0 total lifetime	>10
Design number of cycles	$\leqslant$ 15 000 BPP $\leqslant$ 35 000 EPP	$\leqslant$ 1000
Frequency of plasma disruption	0.15 $cycle^{-1}$ BPP 0.03 $cycle^{-1}$ EPP	$<10^{-4}$/a
VDE	$<2.5\ 10^{-4}$ $cycle^{-1}$	–
Availability	7% BPP 21% EPP	>30%
Pulse duration, s	1000	Steady state

Table 3
Expected erosion rates of Be, W and CFC by sputterisng and off-normal events in ITER

Sputter erosion	Per 1000 s shot	Erosion by off-normal events	Per disruption 100 MJ/m^2	Per slow transient (20 MW/m^2, 10 s) average over life
Be	5 μm	Be (evap. +1/2 melt lost)	75 μm	600 μm
C	0.6–2.4 μm	Be (evap. +1/10 melt lost)	23 μm	300 μm
W	<0.1 μm	C (evap.)	30 μm	10 μm
		W alloy (evap. +1/2 melt lost)	75 μm	~1 μm[a]
		W alloy (evap. +1/10 melt lost)	23 μm	~1 μm[a]

[a]W alloy, assuming initial thickness does not exceed 2 cm. Much higher erosion would occur for larger thickness.

gerous material reducing plasma temperature by radiation. The feasibility of a full tungsten first wall is not clear and might not work. With respect to erosion lifetime we have not only to look for gross-erosion but more for net-erosion which depends on impurity transport. We have to analyze impurity transport to understand net-erosion. We might allow a material with comparable large erosion rates if local redeposition is effective.

2.2. C. Wong

- Comment 1: Under high-neutron fluence, considering radiation damage, I do not see how an ITER first wall with Be, Cu SS combination can be transferred to a DEMO or power plant?
- Comment 2: With respect to Dr Phillipp's comment of avoiding high-Z material to the plasma core, I believe that we should look into the possibility of using very small amounts of high-Z material radiation in the plasma core to distribute the heat flux between the first wall and divertor. This is an experiment showing the possibility of Xe core radiation. The penalty is the reduction of reactivity and the increase of Z_{eff}, therefore higher current drive power. But if the power balance works out, it will have significant advantage in reducing the divertor heat flux.
- Question to Dr Davis: In the US we are going to evaluate different high-power density blanket options. How are we going to address the question of reliability in this type of evaluation?
- Answer: This is a very difficult question. We have to be patient and start the material and component testing program to provide reliability data, before we have confidence in any design.

2.3. H. Maekawa

From the viewpoint of safety analysis, we need to accumulate the activation database due to cascade reactions. We have very little of this type of database, because of lack of high-energy intense neutron source. The high-energy intense neutron source is essential for development of fusion reactors.

2.4. R. Mattas

Materials for plasma facing systems
- Be and C unacceptable because of high erosion
- W is possible but only at low plasma edge temperatures
- Cu is unacceptable with radiation damage concerns and limitation of operating temperature ($T < 300°C$)
- Future directions: Need to look more closely at liquid surfaces for PFC

2.5. R. Behrish

Particle and energy confinement for a fusion plasma has to be sufficiently good but they also have to be limited for being able to extract the alpha energy and the He ash being deposited in the plasma. This power and particle exhaust occurs via particle and energy deposition on the vessel walls. This is the reason for the necessary plasma material interaction. This means we have to find and/or develop materials which are able to stand these particle and energy loads from the plasma. In the early experiments with magnetic plasma confinement, the particle and energy loads were concentrated at relatively small areas on the limiters and later on divertor plates. With the achievement of a radiating cold plasma in the divertor, the power load is less concentrated and the plasma particles reach the vessel walls with lower energies so that sputtering may be largely reduced. The particle load will be D and T and about 10% He which may be implanted with very high fluences and may further diffuse into the PFMs. In addition all plasma facing wall areas are bombarded with energetic neutral hydrogen atoms and some He atoms which are produced by recombination in the plasma and charge exchange processes. If we apply low-Z elements, n-bombardment produced gasses, such as H, D, T, He^3 and He^4 will together with the displacement damage further contribute to a degradation of the plasma facing wall materials.

2.6. K. Sumita

I would like to call your attention on safety of ITER especially to get the licensing of building and site. Though there is no international rule of safety evaluation of an ITER-like fusion machine, we may have some common understanding. Major points are as follows: no-offsite evacuation is optional in any case of accident and incident. I wonder if it may be possible for ITER to have a blanket module in future. Of course it depends on the type of module. Another issue for safety development of low activation materials is very important. Not only for future fusion reactors, I hope ITER will get less radioactive materials and human exposures on maintenance.

2.7. F. Clinard

What is the status of materials selection for the polymeric insulator in the superconducting toroidal field coil? This material presents both a problem and an opportunity – a problem because of its radiation sensitivity, and an opportunity because selection of an optional material may lead to a simplified design and reduced costs.

2.8. R. Aymar

Answer: When considering neutron irradiation issues for the superconducting toroidal field coils, damages to insulation, to superconducting material, to stabilizer (Cu) and mostly the amount of cooling ready to accept, have to be considered simultaneously. As long as helium cooling is a necessity around 4 K, the last issue appears to be largely the most demanding one. High T_c superconductors, if they come one day to be used at this level, will change the picture completely.