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ITER TEST BLANKET MODULE FUNCTIONAL MATERIALS

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GENERAL ATOMICS

DISCLAIMER

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ABSTRACT

Solid breeder and liquid breeder blanket concepts are being developed to be tested in ITER. In addition to the fundamental investigations on the use of reduced activation ferritic/ferritic-martensitic steels (RAFMS) or V-alloys as the structural material, tritium breeder and neutron multiplier materials, and corresponding corrosion issues, there are three classes of functional materials being developed. Performance of these functional materials will impact significantly the performance of respective blanket concepts. Two classes of materials are related to the self-cooled liquid breeder design concepts. The first class is MHD coatings like Er_2O_3 and Y_2O_3, which are proposed as the MHD insulation options required for the self-cooled Li breeder concepts. The second class is flow channel inserts (FCI) like SiC_f/SiC composite material being developed to perform the functions of MHD and thermal insulation for the dual-coolant PbLi concepts. The third class of functional material is the tritium permeation barrier material. This class of material is commonly needed for solid and liquid breeder blanket concepts to reduce the permeation loss of tritium to the environment. Description and development status of these functional materials are described in this paper.

1. INTRODUCTION

In the ITER-test blanket module (TBM) activity, solid breeder and liquid breeder blanket concepts are being developed for testing in ITER. During the assessment of different TBM concepts, many R&D items were identified, including the basic development needs for different structural materials, solid breeders, and neutron multipliers, performance limitations due to corrosion effects were also identified. These are presented in papers of this conference [1–3]. In addition to fundamental material R&D issues three classes of functional materials were identified. Performance of these functional materials will impact significantly the performance of respective blanket concepts. Two classes of materials are related to the self-cooled liquid breeder design concept. The first class are magnetohydrodynamic (MHD) coatings like Er_2O_3 and Y_2O_3, which are proposed as the MHD insulation options required for the self-cooled Li breeder concept. The second class are flow channel insert (FCI) like SiC_f/SiC composite material being developed to perform the functions of MHD and thermal insulation for the dual coolant (DC) PbLi concepts. The third class of functional material is the tritium permeation barrier (TPB) material, which will be needed to reduce the permeation loss of tritium to the environment for both solid breeder and PbLi concepts. This paper presents a summary of different TBM concepts being considered in Section 2. Self-cooled blanket concepts and corresponding design requirements, and development status of MHD coating and FCI are presented in Section 3. TPB requirements and development status are present in Section 4. Conclusions are presented in Section 5.

2. LIQUID BREEDER TBM CONCEPTS

Liquid breeder TBM designs are proposed by different parties. The Russian Federation (RF) is proposing testing of Li-self cooled TBM with Be as the neutron multiplier [4] to enhance the tritium breeding, and vanadium alloys as the structural material. Japan is considering the installation of liquid breeder TBMs such as Li-self cooled TBM without Be, or FLiBe-self cooled TBM in the later period of the ITER operation and testing [5]. The European Union (EU) is focusing on the helium-cooled PbLi concept (HCLL), where helium is used as the primary coolant to extract the blanket power. For higher thermal performance the US is proposing to test a dual coolant PbLi breeder concept (DCLL), where helium is used to cool all RAFMS structures, and the self-cooled breeder is circulating slowly in order to reach a high exit temperature. This concept is also proposed as a blanket option for the EU Power Plant Conceptual Study [6]. China is proposing to test blanket concepts called dual coolant PbLi (DLL) and single coolant PbLi (SLL) designs, which are similar to the DCLL and HCLL concepts, respectively. For the DC designs FCIs are required as thermal and MHD insulators to separate the high temperature PbLi from the lower temperature RAFMS structures. To avoid the MHD issue of the self-cooled concept, Korea is proposing a He-cooled blanket with quasi-stagnant liquid Li as the breeding material (HCML). Its thermal performance is limited by the use of RAFMS.

3. SELF-COOLED BREEDER DESIGNS

For self-cooled breeder concepts there are two basic approaches. The first one is to use liquid Li to perform the tritium breeding and heat removal functions. The second one is the DC concept where helium is used to cool all the RAFMS structures and PbLi is the self-cooled liquid breeder. MHD pressure drop and MHD flow control are critical and common issues for liquid metal self-cooled blanket concepts [7]. The use of MHD insulator barriers to decouple electrically the flowing liquid metal and the wall are necessary to reduce the pressure drop in order to control the system pressure to an acceptable level. In general, for self-cooled blanket concepts, MHD insulators will be needed to reduce the MHD pressure drop with a reduction factor in the range of 10 to 100.

3.1. Li-BREEDER SELF-COOLED DESIGNS

The common advantages of liquid Li cooled concepts originate from the characteristics of pure Li such as high thermal conductivity, high heat capacity, high Li atomic density and low tritium pressure due to its the high solubility of tritium. Compact and simple blankets as shown in Fig. 1 were designed for tokamak power reactors [8,9]. V-alloys such as V-4Cr-4Ti were used as structural material which has a maximum design limit of 700°C. A thermal efficiency of ~40% is projected for the tokamak power reactor design. MHD coatings or FCIs are applied to the internal wall of all Li flowing channels.

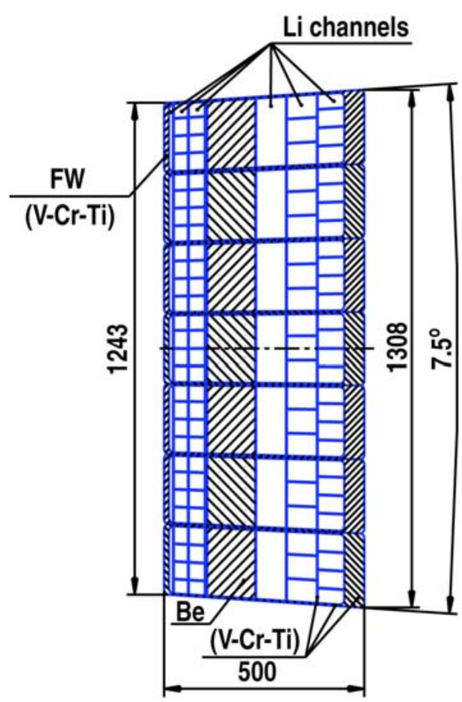

Fig. 1. RF: horizontal cross section of DEMO outboard Li blanket segment, dimensions in millimeters.

3.2. DUAL COOLANT DESIGNS

The DC designs being proposed by the EU, US and China use high pressure helium to cool the RAFMS structure and PbLi as the self-cooled breeder. The basic approach of the DCLL concept is shown in Fig. 2, which shows the use of helium to cool the first wall and all RAFMS structural elements, and the use of FCI elements to perform the key functions of reducing the MHD effect of the circulating PbLi. FCIs made of SiC composite material in the PbLi channels serve as thermal and electric insulators to minimize the MHD pressure loss and reach high coolant exit temperature and, thus, a high efficiency of the power conversion system. The PbLi liquid-metal enters the blanket modules at 460°C and leaves at 650°C to 700°C. The performed MHD calculations show that the pressure drop in the PbLi channels of the blanket due to magnetic/electric resistance is small, if all walls are covered by a SiC electric insulation of 5 mm thickness. When projected for a reference tokamak power reactor design, it has the potential for a gross thermal efficiency of > 40% [10].

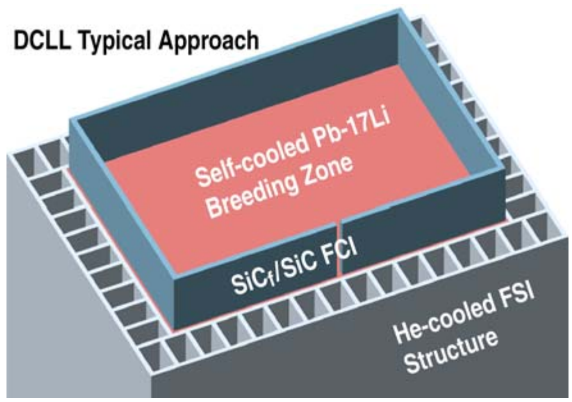

Fig. 2. Dual coolant PbLi FW/blanket (DCLL) concept.

3.3. MHD COATING DESIGN REQUIREMENTS

For MHD coating, a thin ceramics coating on the inner surfaces of the channel wall has been proposed [11,12]. The principal requirement for the coating, in addition to resistivity, is compatibility between the flowing liquid metal and the substrate wall materials. In the case of liquid Li-self cooled blanket with vanadium structures, the highly reducing environment of Li narrows the option of candidate ceramics.

The requirements for the MHD insulator coating for Li/V blanket are [13]:

1. High electrical resistivity, within acceptable property change in the operating environment including radiation effects [14].
2. Chemical stability and compatibility with Li to the maximum operation temperature.
3. Mechanical integrity and thermal expansion match with V-alloy.
4. Safety/environmental characteristics, e.g. low activation.

5. Potential for coating on complex channel configurations.
6. Irradiation resistant.
7. In situ self-healing of any defects that might occur.

3.4. MHD COATING DEVELOPMENT

In Japan, the MHD insulator coating development has been enhanced by domestic programs and a Japan-US collaboration program (JUPITER-II) [15].

Previously, a CaO coating deposited by physical deposition or in-situ coating was one of the leading candidates. However, examination of the material coating showed that they have problems of stability in liquid Li at high temperature [16]. Efforts in recent years were focused on identifying new candidate materials that can withstand Li corrosion at high temperature.

Recently, promising candidate ceramics of Er_2O_3 and Y_2O_3, which were stable to 1073K in liquid Li, were identified by bulk immersion tests [16]. Feasibility of the coating with Er_2O_3 and Y_2O_3 on V-4Cr-4Ti was demonstrated by EB-PVD [17], Arc Source Plasma Deposition [18] and RF sputtering [19]. The crystalline Er_2O_3 coatings produced by Arc Source Plasma deposition were shown to be stable in Li to 1000hr at 800°C [20].

Recent numerical estimates show that tolerable crack density of the coating could be very low [21]. These results encourage the development of double-layer coatings and revisiting of the in-situ healing concepts. Double layers with V on Er_2O_3 showed satisfactory resistivity in molten Li to 600°C [22]. The optimization of compatibility with Li is being investigated.

The in-situ coating method is an attractive technology because it could enable coating on complex surfaces after fabrication of the component and has the potential to heal cracks in the coating without the need to disassemble the component. In addition to the physical deposition methods, in-situ coating with Er_2O_3 on V-4Cr-4Ti is being developed [23]. In this process, a thin insulating layer of Er_2O_3 is formed on V-4Cr-4Ti during its exposure to liquid Li by reaction of pre-charged oxygen in the vanadium alloy substrate and pre-doped Er in Li. Results showed significantly higher stability of the coating compared with the CaO in-situ coating.

In the RF after extensive studies on in-situ formation of AlN and CaO coatings, similar to the direction presented above, the focus is presently on multi-layer and double-layer coatings, where thin layers of insulating material are separated with thin thin layers of V-Cr-Ti. The metallic layer is facing the lithium [24]. Electrical insulation is provided by insulating layers, while the thin V-Cr-Ti layers would prevent lithium penetration into pores of the insulating material and damage its electro-insulating property. The concept was demonstrated in a number of experiments [24–27]. Present RF efforts are directed toward the technology development on the deposition of electro-insulating and metallic layers and the selection of interface layers with good adhesion properties.

3.5. FLOW CHANNEL INSERT DESIGN REQUIREMENTS

The feasibility of SiC_f/SiC FCIs for the DCLL design hinges on the compatibility of the SiC_f/SiC with the PbLi flow at temperatures approaching 800°C (for a DEMO blanket) with characteristic impurities and with characteristic thermal gradients leading to thermal stress loads in the insert. A SiC_f/SiC FCI must satisfy the following requirements:

- Chemically compatible with PbLi at temperatures up to ~800°C in a flowing system and FS at lower temperatures (400°C to 500°C).
- Near 100% dense “sealing layers” or alternate strategy, like double layers, to avoid PbLi soaking into pores of the composite FCI.
- FCI and seal layer must be able to withstand high temperature gradients and primary stresses caused by normal and off-normal tokamak operation events like disruption.
- FCI must be irradiation resistant and show acceptable changes in thermal and electrical conductivity, dimensional changes and structural integrity.
- Selected materials must have favorable safety/environmental characteristics, e.g. low activation.
- FCI can be fabricated to match flow channel geometry.

There is room to optimize the electrical and thermal conductivity of the SiC_f/SiC for the desired application. The requirements of low thermal (target ~ 2 W/mK) and electrical conductivity (target range 1 to 50 S/m), especially in the wall-normal (transverse) direction, indicate that a simpler 2D weave should be considered, and that the matrix infiltration technique should produce closed porosity. Since the fibers and the fiber inter-phase can dominate the conductivity, one should expect lower conductivities in the direction normal to the weave plane, than along it and inter-phase materials and processes should be carefully chosen to minimize unwanted conductivity.

Beyond just the absolute value of the pressure in the channel, changes in properties of the FCIs that lead to changes in the MHD pressure drop can also have large effects on the flow balance between parallel channels. This sensitivity to pressure drop means that moderate changes in FCI electrical insulation property in one channel may lead to large differences in flow rate between parallel channels. This is a significant sensitivity issue for liquid metal blankets. Even if the overall pressure drop is acceptable, for instance cracking and liquid metal penetrations have to be understood both from the material perspective and the subsequent impact on the liquid metal flow. This sensitivity to local changes in electrical conductivity has not yet been fully quantified.

3.6. FCI DEVELOPMENT

SiC_f/SiC composite is a primary candidate material for the FCI due to its properties of chemical compatibility with PbLi and electrical resistivity. The neutron irradiation resistance of advanced SiC_f/SiC is perceived to be able to withstand doses of ~10 dpa [28,29]. However, no experimental data exists for the design goal of 150 to 200 dpa for the fusion power reactor.

The study of the thermal conductivity of SiC_f/SiC composites has been significantly increased in recent years for fusion applications mainly because of the application of advanced radiation-resistant near-stoichiometric SiC fibers, which can provide much higher thermal conduction than conventional SiC-based fibers. Typical through-thickness non-irradiated thermal conductivity for chemically vapor-infiltrated (CVI) SiC-matrix composites with radiation-resistant SiC fibers at 500°C is ~15 W/m-K [30,31]. Under neutron irradiation at the same temperature, its thermal conductivity decreases to a saturation value of 2 to 4 W/m-K at 1 dpa [30–32], which is in the range required for the FCI. Examples of measured and calculated thermal conductivity for non-irradiated and irradiated SiC_f/SiC are shown in Fig. 3, in which a negative temperature dependence of irradiated thermal conductivity is apparent.

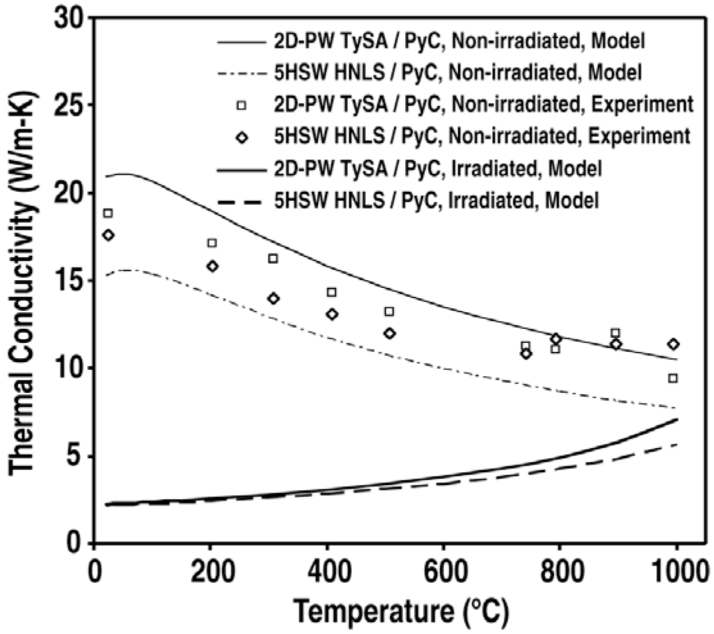

Fig. 3. Experimental and model-predicted temperature dependence of through-thickness thermal conductivity of 2D fusion-grade SiC_f/SiC composites. Note that conductivity of irradiated materials is that calculated for the irradiation temperature.

As to the electrical conductivity for SiC_f/SiC, the through-thickness value is strongly affected by the matrix conductivity. In the fiber direction it is usually dominated by the conduction through the carbon interphase [33,34]. Electrical conductivity of chemically vapor deposited or infiltrated SiC is most commonly determined by the nitrogen and other impurity concentrations, and typically has a range of $1 - 10^4$ S/m at 500°C. Through-thickness electrical conductivity, which is readily achievable for CVI SiC_f/SiC with impurity controlled matrix can achieve the range of 10 – 100 S/m. Fission neutron irradiation may increase or decrease the electrical conductivity. Minor changes have been reported at relatively low doses irradiation [32].

Although primary stresses on the FCI panel may be insignificant, through-thickness thermal stress could be substantial due to high temperature gradient. Furthermore, SiC develops negative temperature dependent volumetric expansion under irradiation at temperatures below ~1000°C [35]. Therefore, the internal stresses arise not only from thermal expansion but also from differential swelling. At a temperature range of 400°C to 600°C, the internal stress due to differential swelling can be a major integrity issue for SiC_f/SiC FCI, because it can be roughly twice as high as the thermal stress. This can exceed typical matrix cracking stresses of CVI SiC_f/SiC depending on design parameters, state of mechanical constraint, and properties of the FCI itself.

FCI R&D is therefore directed toward material development and material/architectural design for low thermal and electrical conductivity while maintaining tolerance against through-thickness temperature gradient and neutron irradiation. Porus-midplane two-dimensional SiC_f/SiC, which was previously proposed as an FCI material option with enhanced insulations, may not be appropriate due to insufficient inter-laminar shear strength. Alternate approaches including the incorporation of insulated second layer are being considered. Major technical challenges are associated with neutron irradiation effects. Such as the drastic decrease in thermal conductivity of SiC at low neutron fluence, electrical conductivity can also be sensitive to very low dose irradiation and the differential swelling of the composite. The irradiation effect on the thermal conductivity of SiC_f/SiC is relatively well-addressed [30], whereas the effect on electrical conductivity of high-resistivity grade SiC is being studied in the HFIR 18J experiment [36]. A second layer insulation could minimize the irradiation effects on the conductivity of the base material. For the assessment of mechanical integrity issues, the primary goal is to understand the irradiation creep of SiC and composites [37]. Irradiation issues that are specific to the fusion neutron spectrum, such as transmutation and burn-up and the corresponding impacts on electrical conductivity and chemical compatibility with liquid metal can be partly addressed by integrated testing in ITER. Additional fundamental understanding can be supported by fission reactor irradiation with various experimental techniques.

4. TRITIUM PERMEATION BARRIER

The third class of functional material is the TPB material, which will be needed to reduce the permeation loss of tritium to the environment for both solid breeder and PbLi concepts. It is needed for PbLi breeder because of its property of low tritium solubility. The site release limit of tritium for a particular fusion reactor site will depend on the local regulation and presently is set up for the ITER at 1 g/y (i.e. 27 Ci/d) [38]. The determination of a required tritium permeation reduction factor (PRF) to achieve this limit is a complex task which needs to take into account a number of factors (e.g. PbLi flow rate, efficiency of tritium extraction from PbLi and from He coolant, helium flow rate in the coolant purification system, design of a steam generator (SG), leak rate in the He coolant system, etc.). Presently, the target PRF for the EU HCLL breeder DEMO blanket components in contact with PbLi should be at least in the range of 10 to 50. In the SG, natural oxides based anti-permeation barriers should exhibit PRF higher than 100 [39].

4.1. REQUIREMENTS

The requirements for the TPB are very similar to the MHD coating, but with different functions. The requirements for the TPB for solid and PbLi blankets are:

1. High tritium permeation resistance or PRF.
2. Chemical stability/compatibility with adjacent environment like He or PbLi at operating temperatures, thermal cycle and environment.
3. Mechanical integrity/thermal expansion matches with the substrate material and crack resistant.
4. Irradiation resistance.
5. Safety/environmental characteristics, e.g. low activation.
6. Potential for coating on complex internal or external channel configurations.
7. Potential for in situ self-healing of any defects that might occur.

4.2. DEVELOPMENT IN THE EU

The design of the EU HCLL DEMO breeder blanket incorporates a TPB on the blanket module surfaces in order to limit tritium permeation into the Helium Coolant System. The performance of such TPB should be tested in the respective ITER TBM. Aluminum rich coatings forming Al_2O_3 at the surface were studied for several years as TPB in the European Fusion Technology Program [40]. Hot-dip aluminization (HDA) [41–43], chemical vapor deposition (CVD) [44] and physical vapor deposition (PVD) [45] are being used as deposition techniques and briefly discussed in the following.

In the HDA process [41–43] the RAFM steel (EUROFER) to be coated is dipped into liquid Al heated up to 700°C for 30 s and cooled down in an Ar-5%H_2 atmosphere. Afterwards the standard heat treatment of EUROFER is applied to the specimens. The microstructure of the coated layer consists of an outer FeAl layer and an inner α-Fe(Al) phase. Overall thickness of the layer is about 120 to 150 μm.

The CVD process is performed in two steps [44]:

- Deposition of FeAl layer by pack-cementation.
- Deposition of Al_2O_3 on top by metal-organic CVD method.

The cement for the powder-pack process consists of a mixture of donor (Fe+Al), activator and Al_2O_3 powder as inert filler. The deposition temperature is set to 750°C for 2 h at an Ar pressure < 1 kPa. The Al_2O_3 deposition is achieved by decomposition of a metal-organic precursor at < 500°C for 2 h. SEM analysis shows that the CVD coated layer forms three sub-layers: Fe_3Al, FeAl (together about 6.5 μm) and Al_2O_3 (~1 μm) on the top.

A 1 μm thick crystalline alumina α-Al_2O_3 coating is produced on the substrate surface by a PVD process [45]. The deposition is performed by an arc discharge using an aluminum cathode, filtering metal droplets from the plasma and introducing oxygen into the main chamber. The advantage of the technique developed (at a bias voltage of –200V) is the relatively low temperature of the substrate of 700°C needed to produce α-alumina compared to the usual 1000°C.

The HDA and CVD aluminum coatings on EUROFER were tested in ENEA-Brasimone in hydrogen gas and in Pb-15.7Li alloy [46]. The measured PRFs did by far not fulfill the requirements. SEM examinations showed detachment of the coatings and cracks. It was therefore concluded that the HDA and CVD processes did not reach the required technological maturity and that further R&D effort is still needed.

Experiments on deuterium permeation through EUROFER coated by α-alumina were performed by IPP Garching [45]. The permeation tests with coated and uncoated EUROFER specimens were done in the temperature range of 300°C to 600°C at pressures of 10^3 to 10^5 Pa, but the temperatures of the coated samples had to be chosen higher (up to 800°C) to enable detection of permeated deuterium with the available quadrupole mass spectrometry (QMS). The measured PRF is 10^3 or even higher. In addition to the very good permeation results the α-alumina layer demonstrated a high structural stability with respect to thermal cycles up to 800°C.

The main directions in the development of suitable anti-permeation coatings in the EU are as follows:

- Further R&D for development of AlFe-based anti-permeation coatings and of W anti-corrosion coatings, which can serve also as an anti-permeation barrier, for TBM parts that are in contact with PbLi.

- Development of new advanced coating processes (e.g. galvanic deposition of aluminum, electro-spark deposition, CVD) to achieve required quality, reproducibility and PRF (in the range of 10 to 50), and taking into account the geometrical constraints of breeder blanket components.
- Qualification of the developed coatings in terms of compatibility with PbLi thermo-mechanical stability, protium/deuterium permeation characteristics, irradiation performance and activation in fusion spectra.
- Development of natural oxide based anti-permeation barriers on the SG Inconel/Incoloy inner surfaces and alternatively on the cooling and stiffening plates inner surfaces from the He coolant side. Determination of proper He coolant conditioning (e.g. ratio of hydrogen and water vapor) in order to achieve thermo-mechanical stability and required PRF.

5. CONCLUSIONS

Three classes of functional materials have been identified. Performance of these materials is crucial to the performance of TBM concepts being developed to be tested in ITER. They are the MHD coatings, FCI and TPB. Design requirements of these functional materials have been identified. Possible material options have also been identified. Intense R&D efforts in Japan, EU, RF and the US have been initiated. Some encouraging results have been obtained, but these developments are still in their infancy. In addition to basic performance, critical uncertainties are also in the area of irradiation effects and corresponding material property changes. With the common interest in the development of similar blanket concepts among ITER participation nations, increased effort, collaboration and coordination in this area of development are encouraged and expected. ITER testing is a necessary integrated testing step, but due to ITER's limited fluence capability, independent fusion spectrum testing facilities like the IFMIF and Components Testing Facility (CTF) will be needed.

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