

# **EFDA WORKPROGRAMME 2011**

## **Call for Participation**

**(Part of the EFDA WP, PPP&T)**

**DEMO Design Assessment Studies**

**Deadline for Responses: 07. Jul 2011**

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This Call for Participation aims to implement part of the Power Plant Physics and Technology Work Programme for 2011 under Task Agreements as foreseen in the new EFDA Art. 5

## **Introduction**

At its 47th meeting in Budapest (Hungary) on the 21st and 22nd of March 2011, the EFDA Steering Committee approved the amendment to the EFDA 2011 Work Programme concerning the activities associated with the newly established Power Plant Physics and Technology (PPPT) Department under EFDA.

This Call relates to the preparation of six Task Agreements covering a number of assessment work packages on a limited number of important engineering topics, which are viewed as bearing a strong impact on the future conceptual design activities.

1. Technological maturity/development needs of Heating and Current Drive and Fuelling and Pumping Systems for DEMO (*WP11-DAS-HCD*);
2. Status and prospects of high temperature superconducting magnets (*WP11-DAS-HTS*);
3. Current conceptual solutions for DEMO divertor and breeding blanket including an assessment of the coolants for in-vessel components (*WP11-DAS-IVCC*);
4. Material Database status and needs for DEMO conceptual design activities (*WP11-DAS-MAT*);
5. Technology/engineering issues associated with pulsed tokamaks (*WP11-DAS-PLS*);
6. Candidate remote maintenance schemes and solutions (*WP11-DAS-RH*).

## Programmatic Background

The goals of these assessments are (i) to revisit the rationale and technology development assumptions that have led to the selection of some design choices in the past; (ii) to assess their technological maturity and/ or development prospects in view of recent factual information; and finally (iii) to provide a provisional roadmap for possible realistic developments in the various areas, with an estimate of the resources needed.

A number of preparatory meetings involving experts of Associations and Industry and with the help of relevant EFDA Topical Groups and Coordinating Committees have taken place during the last two months and they have been extremely useful to prepare a Terms of Reference for each of the areas above and which are attached here. These terms of reference describe the review assignment work that need to be conducted and are intended to provide a clear definition of (i) specific questions to be addressed in the course of the study to be carried out via EFDA tasks to be launched shortly after the meeting; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

For the purpose of this review work and similar to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degrees of extrapolation from the current known underlying physics and engineering basis should be considered:

- DEMO Model 1: a “conservative baseline design” i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.
- DEMO Model 2: an “optimistic” design, i.e. a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

A preliminary set of technical parameters describing these two options is being prepared and will be issued at the time of the approval of this task agreement. These parameters will be defined to allow assessments to begin and should not be considered as reference EU DEMO designs. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters. In addition, these parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted as part of the PPPT WP in 2011.

The description of the activities to be conducted in each area together with a definition of the resources to be allocated is described under each Task Agreement below.

# 1. HCD-FP systems for DEMO:

## Task Agreement WP11-DAS-HCD:

### Assessment of the HCD-FP systems for DEMO

#### 1.1 Introduction

A review work of the heating and current drive & fuelling and pumping (HCD-FP) systems will be conducted based on the two DEMO options described in the Programmatic Background. These options provide the plasma parameters required to define the role of the different HCD-FP systems in all phases of the plasma evolution, from creation, to control and to termination of the burning plasma. A second element of the review work is to critically analyze the technology of the HCD-FP systems in terms of the DEMO Reliability, Availability, Maintainability and Inspectability (RAMI) requirements. The third and final part of the review work is to produce a well justified roadmap demonstrating the realizability of the HCD-FP systems in a time frame consistent with the preparation and construction of a DEMO reactor.

#### 1.2 Objectives

A table of contents (ToC) of the HCD-FP assessment report has been prepared providing the same structured analysis for all the HCD-FP systems and allowing for a bipartisan reporting. This ToC is organized in three main sections. The relation to the burning plasma is considered first, with a description of the role of the HCD-FP system in the two DEMO options. This section of the report will include a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis table to be developed based on factual information (e.g., coupling LH, ICH to H-mode plasma Etc.)

The second section of the ToC calls for a review of the technology involved in the HCD-FP systems making a distinction, whenever possible, between issues which are scenario dependent and those that instead are scenario-independent. The capabilities of the individual components of the systems mainly from the stand point of (mainly) current drive efficiency will be demonstrated through a RAMI analysis. This section defines the core part of the assignments. The physics involved in the major components will be described as well as the state of understanding and numerical code availability.

The third section of the report relates to the identification of the main differences between ITER and the DEMO options from the HCD-FP standpoint and includes a gap analysis and the proposals for PPPT mandatory activities to have the HCD-FP systems ready in time for a DEMO reactor.

#### 1.3 Work Description and Breakdown

##### *Structure*

##### *Work Breakdown*

### WP11-DAS-HCD-EC

#### Assessment of ECCD for DEMO

Perform the physics and technology assessment for the DEMO model 1 and model 2, considering available technological solutions as well as longer term solution. The analysis should be well documented either by simulations or better by experiments.

**EC1 General coordination and physics analysis (0.2 ppy PS)** : This work package includes the general coordination of the assessment of the EC system. It also includes the study of DEMO specific physics requirements: scenarios, power coupling, choice of frequency. This task also calls for a SWOT analysis of the EC system.

**EC2 Technology requirements (0.3 ppy PS)**: The objective of this activity is to analyse the EC specific R&D needs and EC development roadmap, the technology requirements as well as specifications for nuclear environment: power, source, transmission lines, RF windows, antenna, diagnostics, interfaces, remote handling issues. Efficiency of the EC in DEMO will be discussed. The activity includes a preliminary RAMI analysis.

Please specify the acronym (EC1 etc. ) in your reply.

## **WP11-DAS-HCD-FP**

### **Assessment of the Fuelling-Pumping systems for DEMO**

Perform the physics and technology assessment for the DEMO model 1 and model 2, considering available technological solutions as well as longer term solution. The analysis should be documented by simulations.

#### **Fuelling system**

**F1 General coordination (0.2 ppy PS)**: Besides the general coordination of the assessment of the Fuelling systems, the work package calls for a SWOT and a preliminary RAMI analysis and for a roadmap of developments of fuelling systems for DEMO model 1 and DEMO model 2.

**F2 Physics aspects of DEMO fuelling (0.1 ppy PS)**: This work package calls for an analysis of the physics knowledge in the area of fuelling in particular for DEMO model 1 and model 2 conditions. The objectives of this activity are to identify efficient core and edge fuelling methods and their impact on a reactor design (poloidal and toroidal distributions; magnetic connection) and to test whenever possible their scaling up from ITER. The work includes an analysis of the status of code development needs.

#### **Pumping system**

**P1 General coordination (0.1 ppy PS)**: The assessment of the pumping systems will be made by comparing available technical options by pairs to come to unbiased results and link this with the SWOT approach. Some input are however lacking to scale the physics parameter to a throughput. Therefore the analysis will be given for a range of acceptable values only. Also important is the divertor and the achievable neutral pressures in its area whose impact on the pumping will be analyzed. The work package also calls for a roadmap for the development of pumping systems for DEMO.

**P2 Assessment of physics code for determining the pumping capabilities (0.1 ppy PS)**: Extrapolation of the pumping system from ITER to DEMO will be difficult. Therefore tools such as numerical codes are needed to understand physics issues linked to the divertor and pumping geometries. This work package calls for an analysis or the needs in code development, and experimental testing for an integrated pumping system design in DEMO. The work package also calls for an analysis of the role of the pumping system in controlling the plasma performance.

Please specify the acronym (F1, P2 etc. ) in your reply.

## WP11-DAS-HCD-IC

### Assessment of the ICCH and ICCH for DEMO

Perform the physics and technology assessment for the DEMO model 1 and model 2, considering available technological solutions as well as longer term solution. The analysis should be well documented either by simulations or better by experiments.

**IC1 Coordination of the assessment work and of the physics studies except High Frequency Fast Wave Current Drive (HFFWCD) (0.2 ppy PS):** Besides the general coordination of the assessment, this work package includes the review of the physics of IC in DEMO model 1 and 2 (species heated, current drive expected) based on extrapolation using existing database, ITER design and simple formulas. For DEMO model 1, the main emphasis of this work package will be given to scenarios 2 fcT in D-T-(3He), ion heating, tails (through a QLFP analysis), CD windows, and frequency range, and includes an assessment of the coupling for an ITER-type antenna (ITER-like scrape-off) and the extrapolation from the CD database. For DEMO model 2, the objectives are to establish basic physics feasibility of a current drive scheme, assess  $f$  range,  $k//$  requirements, and to provide first estimates of CD efficiency for a limited number of cases. The study will conclude for the DEMO model 1 case by proposals for refined theoretical investigations and for experiments, in particular for benchmark test of current drive at relevant  $T_e$  on a large tokamak, arc detection and sheath studies. For the DEMO model 2 case, proposals for a longer term program will be made to more accurately describe the high frequency fast wave scheme and on the validation of new launcher concepts.

**IC2 Coordination of the assessment of the technology of IC (0.1 ppy PS):** The objectives of this work package are to identify suitable power source and transmission system, outline a launcher design and revisit the arc detection and sheath effects, materials to be used and utilities. Part of work will be devoted to define a design and R&D program for building and testing the IC systems.

**IC3 High Frequency Fast Wave Current Drive (HFFWCD) (0.1 ppy PS):** The HFFWCD system is considered for DEMO model 2 for broad profile full CD. This work package will develop the physics of the scheme, establish basic physics feasibility, assess  $f$  range,  $k//$  requirements, and provide first estimates of CD efficiency. Also included in this work package is a review of high harmonics FW experiments (on NSTX) and an assessment of their relevance to HFFWCD, an analysis of possible launcher designs and concept and finally the outline of an experimental program.

**IC4 SWOT and Preliminary RAMI analysis (0.1 ppy PS):** This work package is to demonstrate the performance of the IC systems in particular through the SWOT and preliminary RAMI analysis for DEMO model 1 and model 2.

Please specify the acronym (IC1 etc. ) in your reply.

## WP11-DAS-HCD-LH

### Assessment of LHCD for DEMO

Perform the physics and technology assessment for the DEMO model 1 and model 2, considering available technological solutions as well as longer term solution. The analysis should be well documented either by simulations or better by experiments.

**LH1 General coordination and physics analysis (0.1 ppy PS):** This work package includes the general coordination of the assessment of the LH system.

**LH2 LH Physics analysis (0.2 ppy PS):** This task calls for a study of DEMO specific physics requirements: scenarios, power coupling, choice of frequency (versus power density, alpha

parasitic absorption). This physics analysis task will be consolidated through discussions with the other Coordination Committees. This task includes all activities needed for the SWOT analysis of the LH system.

**LH3 Specific technology study (0.2 ppy PS):** The objective of this activity is to analyse the LHCD specific R&D needs and technology requirements and specifications for nuclear environment: power, source, transmission lines, RF windows, antenna, diagnostics, interfaces, remote handling issues. The study includes a preliminary RAMI analysis and an analysis of LHCD operation in DEMO nuclear environment looking e.g. at full system integration, system monitoring/control/protection, CODAC, and real-time control.

Please specify the acronym (LH1 etc. ) in your reply.

## **WP11-DAS-HCD-NBI**

### **Assessment of the NBI for DEMO**

Perform the physics and technology assessment for the DEMO model 1 and model 2, considering available technological solutions as well as longer term solution. The analysis should be well documented either by simulations or better by experiments.

**NB1 General coordination and physics analysis (0.2 ppy PS):** This work package includes, besides the coordination of the assessment of the neutral beam for DEMO model 1 and model 2, an assessment of the heating requirements to drive plasma to burn condition, including dependence on power waveform, an investigation of the current drive sensitivity to beam size and beam energy, power density, position and inclination angle, an assessment of sensitivity to scenario and a SWOT assessment of functionality. Included in this work package is the Development & Roadmap, based on critical issues, differentiation of the DEMO N-NBI from ITER system and should include recommendations for R&D, priorities, timescales and roadmap

**NB2 Coordination of the assessment of the technology (0.1 ppy PS):** The objectives of this work package are to assess the injector configuration and its optimisation (size, inclination angle/beamline length, port number), the shielding (radiation & magnetic), the materials to be used in terms of creep & fatigue and irradiation, the utilities (cooling, cryogenics). Included here is the analysis of the N-NBI in terms of efficiency, and the SWOT and preliminary RAMI analysis of the technology.

**NB3 Voltage holding and accelerator (0.1 ppy PS):** This task calls for an analysis of the voltage holding and accelerator configuration, through a reviewing of the recent modification of the ITER NBI system and linking to the prescription for a DEMO reactor.

**NB4 Cs management (0.1 ppy PS):** This work package calls for an assessment of ion sources from the point of view of the physics involved and of geometrical aspects. The Cs management should be emphasized for its direct impact in the preliminary RAMI analysis (e.g. cleaning every year). Status of the code development effort for physics understanding and for ion source management should be included in the study.

Please specify the acronym (NB1 etc. ) in your reply.

### ***JET related activities***

Not applicable.

## ***Resources***

The total resources available is 2.5 PPY under Priority Support.

## **1.4 Scientific and Technical Reports**

The five Coordination Committees (CCIC, CCLH, CCEC, CCNB and CCFP) will provide assistance for the review activities and for the redaction of a final report due at the end of 2011.

### ***Progress reports***

At the end of the Task Agreement during the final monitoring meeting, the task responsables shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

### ***Report of achievements under Priority Support***

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

## ***Milestones and Deliverables***

Milestones:

M1 - Kick off Meeting to organize the work

M2 - Interim Progress Meeting to assess the status of the work and provide guidance for integration of the studies

M3 - Final meeting

Deliverables:

The deliverable is one document per HCD-FP system produced according to the **Structure of the assessment report (see [2])**.

The reports should be accompanied by an executive summary including the key findings and recommendations.

The deliverables for each activity are:

- An interim report by October 2011
- A final report by December 2011

***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, *EFDA (11) 47/4.1.1*, 9 March 2011.

[2] Terms of Reference: Review of technological maturity/development needs of heating and current drive & fuelling and pumping systems for DEMO, 25.5.2011 (ToR\_HCD: EFDA\_D\_2LP272)

## 2. High Temperature Superconductors for Fusion Applications:

### Task Agreement WP11-DAS-HTS:

#### Evaluation of the Status and Prospects of High Temperature Superconducting Magnets for Possible Potential Applications in Future Fusion Reactors

### 2.1 Introduction

High-temperature superconductors (HTS) have the potential to enable operation at higher magnetic fields ( $> 14\text{T}$ ) at much higher temperatures (up to  $50\text{ K}$ ) in the fusion geometry than conventional superconductors.

In particular, enabling operation at high magnetic fields with good temperature tolerance is perceived to be an important advantage in a DEMO reactor especially to compensate/mitigate potential performance shortfall risks that may arise from the fact that reliable operating scenario at high density (i.e.,  $n > n_G$  - Greenwald limit) could be difficult to be established, and this in the absence of compensating measures with coil design that operate at high fields would translate into the inability to achieve significant level of fusion power in a reactor.

Recent developments show promises that novel high temperature superconductors may become available with high critical currents and magnetic field capabilities as required for fusion applications. In the largest part this research is beyond the scope of the fusion programme and still in the fundamental phase requiring significant research before it can be employed reliably in fusion devices. For example, in high-temperature superconductors, quench propagation slows about three orders of magnitude from  $10\text{m/s}$  to  $10\text{mm/s}$ , requiring development and integration of new techniques for quench detection. On the other hand using magnets at temperature  $> 50\text{ K}$  could allow omitting the LN<sub>2</sub> thermal shield saving significantly cooling power and improving availability which would increase the performance of a future fusion reactor significantly and simplifies the machine.

### 2.2 Objectives

To review the technology maturity of HTS for fusion application.

The following tasks should be addressed:

- Review of various solutions investigated in the past
- Clearly identify the potential of these options, and the associated design development issues, to operate at high fields
- Provide recommendations and a work plan for further research to be carried out distinguishing from small scale lab test to medium scale prototype test
- Identify areas where industry should be involved
- Provide a tentative roadmap with estimate of resources needed to carry out the work plan with a breakdown into elementary activities

## 2.3 Work Description and Breakdown

### *Structure*

#### *Work Breakdown*

### **WP11-DAS-HTS-01**

#### **Task Coordination**

Task Coordination

Available resources: 0.2 ppy Priority Support

### **WP11-DAS-HTS-02**

#### **Assessment of HTS material, scalable cabling concepts**

Assessment of HTS material, scalable cabling concepts incl. demonstration, mechanical cable strength and cooling concepts

- HTS material survey and usability for fusion
- Scalable cabling concepts for currents in the tens kA range (>20kA)
- Mechanical strength to withstand electromagnetic forces
- Cooling requirement and concepts
- Demonstration of scalable cabling concepts
- Resource and schedule definition

Available resources: 0.7 ppy Priority Support

### **WP11-DAS-HTS-03**

#### **Assessment of influence of fast neutron irradiation on RE-123 material**

Assessment of influence of fast neutron irradiation on RE-123 material incl. check of homogeneity of current flow in coated conductor

- Influence of fast neutron irradiation on the performance of RE-123 coated conductors incl. update of the corresponding data base
- Comparison to results with Nb<sub>3</sub>Sn
- Assess the need of replacing Y by another RE
- Assess the homogeneity of current flow in coated conductor tapes and cables
- Resource and schedule definition

Available resources: 0.2 ppy Priority Support

### **WP11-DAS-HTS-04**

#### **Assessment of electrical stabilization, quench protection and characterization of samples**

Assessment of electrical stabilization, quench protection incl. He-gas cooled cable designs and characterization of full size samples & small insert coils incl. test of straight HTS samples

- Definition of appropriate combinations of operating current, temperature, and field (aiming at operation field > 14T)
- Option for relatively high field in connection with operation temperatures of 4.5 K and 27 K (cooling by neon possible)
- Electrical stabilization
- Quench protection incl. He-gas cooled cable designs
- Characterization of full size samples and small insert coils incl. test of straight HTS samples (I > 10 kA, B > 10 T)
- Resource and schedule definition
- Compare performance and cost of industrially fabricated MgB<sub>2</sub> wires with NbTi.
- HTS material survey and usability for fusion
- Resource and schedule definition

Available resources: 0.3 ppy Priority Support

## **WP11-DAS-HTS-05**

### **Assessment for RE-123 fusion cable joints**

Assessment for RE-123 fusion cable joints

- Review the state of the art of the joint solutions for REBCO cable
- Joint fabrication trials
- Industry solutions to join HTS conductors and possibilities to scale for fusion application
- Modelling of joint concept in optimising heat load
- Compare the performance and the cost of industrially fabricated
- Resource and schedule definition

Available resources: 0.2 ppy Priority Support

## **WP11-DAS-HTS-06**

### **Assessment of RE-123 fusion cable with low ac losses**

Assessment of RE-123 fusion cable with low ac losses

- AC loss in scalable RE-123 cables incl. Roebel cables – theory, modelling, manufacturing and experiments for frequencies <10 Hz
- AC loss optimization and characterization - responses to external field variations or several per cent current variations (kA) below 10 Hz.
- Reference testing conditions for ac loss determination in HTS cables
- Numerical methods for ac loss estimation incl. coupling loss and DC non-uniform current distribution modeling Resource and schedule definition
- Resource and schedule definition

Available resources: 0.2 ppy Priority Support

## WP11-DAS-HTS-07

### Assessment of strain effects on a possible RE-123 high field, high current cable

Assessment of strain effects on a possible RE-123 high field, high current cable

- Transport properties and strain load in wires and various cable layouts
- Influence of transverse and axial load on transport properties under operating conditions
- Transport properties of wires under periodic bending, spatial (periodic point contact) and homogeneous transverse load, axial tensile and compressive strain
- Tensile stress-strain characterization and crack analysis (SEM) of wires and cables
- Experimental study of mechanical properties of cabled structures under cyclic transverse and axial load
- Intrastrand resistance measurement
- Resource and schedule definition

Available resources: 0.2 ppy Priority Support

#### *JET related activities*

Not applicable.

#### *Resources*

The total resources available will be up to 2 ppy under Priority Support.

## 2.4 Scientific and Technical Reports

### *Progress reports*

At the end of the Task Agreement during the final monitoring meeting, the task responsables shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

### *Report of achievements under Priority Support*

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

### ***Milestones and Deliverables***

Milestones:

M1 - Kick off Meeting to organize the work

M2 - Interim Progress Meeting to assess the status of the work and provide guidance for integration of the studies

M3 - Final meeting

Deliverables:

The deliverables for this activity are:

- An interim report by October 2011
- A final report by December 2011

The report shall address all the specific points identified in the Terms of Reference. In addition, the report shall cover and integrate the following items in the answers:

- i) assessment of industrial status of HTS cables and magnets and perspectives for future industrial developments
- ii) assessment of research status and perspectives of developing HTS for fusion applications
- iii) identification of common areas and prospects of collaboration between industry and fusion
- v) roadmap and workplan for 2012 (breakdown into activity list with resources and timeline, including dates and description for deliverables and milestones)

The reports should be accompanied by an executive summary including the key findings and recommendations.

### ***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, *EFDA (11) 47/4.1.1*, 9 March 2011.

[3] Terms of Reference: Evaluation of the status and prospects of high temperature superconducting (HTS) magnets for possible potential applications in future fusion reactors (ToR HTSC: EFDA\_D\_2LP3CX)

### 3. In-vessel Component Coolants:

**Task Agreement WP11-DAS-IVCC:**

**Current Conceptual Solutions for DEMO Divertor and Breeding Blanket including an Assessment of the Coolants for In-Vessel Components**

#### 3.1 Introduction

To enhance the efficiency of the energy production within DEMO, there is a need to utilise coolants for the blanket and divertor that may sustain elevated operating temperatures. However, the selection of a suitable coolant is made difficult by the number of many factors that must be considered, such as thermal and radiation stability, required pumping power, compatibility with structural materials, coolant availability, economics.

Although alternative coolants are being considered, the most credible options for DEMO are helium and water. The two options have been considered in the PPCS study regarding the liquid breeder. The development of high temperature He-cooling technologies is very demanding. While non-fusion specific technologies (pressurization and He circulation) might be developed for fission projects, some fusion specific R&D issues need to be addressed. In particular He-cooled in-vessel components, such as the He-cooled W-divertor project has been pursued at KIT and ENEA . It is however far from certain that He-related R&D will be successfully completed in time for DEMO. Water-cooled divertor concepts have been developed allowing maximum incident fluxes up to 15 - 20 MW/m<sup>2</sup> . However, the behaviour under irradiation of some considered materials (CuCrZr, Graphite, ...) is questionable, and a water-cooled divertor concept which uses steel (e.g., EUROFER) as a heat sink material and W as armour is limited to a much lower maximum incident flux. Nevertheless, It would be appropriate to consider the credibility of possible back-up options, i.e. a water cooled DEMO, and the required R&D. The main concern in this case is the EUROFER embrittlement at around 300oC and the safety concerns related to the water–LiPb reaction in case of accident.

Finally, while there would be significant benefits in operating DEMO and reactors at relatively high first-wall temperatures (in the range 300–500 oC, depending on the cooling options He or water), it should be pointed out that first wall temperatures in all tokamaks presently operating or foreseen (including ITER) are in the range 200–300oC. No foreseen device will therefore provide demonstration of in-vessel operation in DEMO relevant ranges of plasma facing component temperatures. This is a significant gap in the fusion programme worldwide, which needs to be filled.

#### 3.2 Objectives

A review assignment work is proposed to be performed to determine the status and prospects of design concepts and the R&D needs of in-vessel components associated in particular with the selection of coolants.

#### 3.3 Work Description and Breakdown

##### *Structure*

The analyses will take into account work done in the past in this area (see references in [4]) and review the technical solutions that have been proposed.

**Work Breakdown**

**WP11-DAS-IVCC-01**

**Working Group Coordination**

Coordination of the assessment, ensuring no overlap with the Working Groups considering materials and Issues of Pulses Device and Activity on a Feasibility study of a water-cooled divertor for DEMO based on the optimisation of the ITER W-monoblock design and technology. This latter activity is covered in 2011 by another call (CfP-WP11-PEX-01).

Available resources: 0.2 ppy under Priority Support

**WP11-DAS-IVCC-02**

**DEMO relevancy of the ITER TBM programme**

Review what can be gained from ITER regarding the blanket concepts; analyse the DEMO relevancy of the Test blanket Modules to be implemented in ITER. Conduct a risk analysis, by identifying the main risks and impacts and conducting a risk mitigation strategy.

Available resources: 0.2 ppy under Priority Support

**WP11-DAS-IVCC-03**

**Availability of helium**

Carry out a literature review to determine the availability of helium supplies in the future.

Available resources: 0.2 ppy under Priority Support

**WP11-DAS-IVCC-04**

**Development of helium systems**

Review the current status and perspectives of the development of the helium systems, in particular in the frame of Generation IV. Identify possible development synergies with the fission area.

Available resources: 0.2 ppy under Priority Support

**WP11-DAS-IVCC-05**

**Water-cooled blanket concept issues**

Identify the issues identified during past studies regarding water-cooled blanket concepts. Review the rationale and technology development considerations that have led to the exclusion of water-cooled blanket options for DEMO.

Available resources: 0.2 ppy under Priority Support

**WP11-DAS-IVCC-06**

**R&D for helium-cooled blanket concepts**

Revisit the rationale and technology development assumptions that have led to the selection of current He-cooled blanket design concepts. Identify main R&D issues and elaborate a provisional roadmap for possible realistic developments in the various areas, with an estimate of the resources needed.

Available resources: 0.2 ppy under Priority Support

### **WP11-DAS-IVCC-07**

#### **Risk analysis for blanket concepts**

Perform a risk analysis for the possible blanket concepts for DEMO Model 1 and Model 2, based on technological aspects. Establish a risk register.

Available resources: 0.2 ppy under Priority Support

### **WP11-DAS-IVCC-08**

#### **Review of water-cooled divertor concepts**

Review the water-cooled divertor concepts studied in the past, giving the performance limitations related to the various heat sink and structural materials [It should be noted that a specific task focussing on an ITER-like technology is defined in another call (CfP-WP11-PEX-01)].

Available resources: 0.3 ppy under Priority Support

### **WP11-DAS-IVCC-09**

#### **Helium-cooled divertor**

Review status and perspectives of the development of the helium-cooled divertor. Identify main R&D issues, performance limitations and elaborate a provisional roadmap for possible developments with an estimate of the resources needed.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-IVCC-10**

#### **Risk analysis for possible divertor concepts**

Perform a risk analysis for the possible divertor concepts for DEMO Model 1 and Model 2, based on technological aspects. Establish a risk register.

Available resources: 0.2 ppy under Priority Support

#### ***JET related activities***

Not applicable.

### ***Resources***

The total resources available are 2.0 ppy under Priority Support.

## **3.4 Scientific and Technical Reports**

### ***Progress reports***

At the end of the Task Agreement during the final monitoring meeting, the task responsables shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

### ***Report of achievements under Priority Support***

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

### ***Milestones and Deliverables***

Milestones:

M1 Kick-off meeting

M2 Discretionary review meeting (July - Oct)

M3 Final meeting (Nov - Dec) - presentation and review of the results obtained during the analysis of the in-vessel coolants for DEMO.

Deliverables:

The deliverables for this activity are:

- An interim report by October 2011
- A final report by December 2011

The reports should be accompanied by an executive summary including the key findings and recommendations.

***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, *EFDA (11) 47/4.1.1*, 9 March 2011.

[4] Terms of Reference: Evaluation of current conceptual solutions for DEMO divertor and breeding blanket including an assessment of the coolants for in-vessel components (ToR\_IVC\_Coolants: EFDA\_D\_2LP3GV).

## 4. Materials database for DEMO:

### Task Agreement WP11-DAS-MAT:

#### Material Database status and needs for DEMO conceptual design activities

#### 4.1 Introduction

The main goal of this task agreement is to review the material database status and need for DEMO Conceptual Design Activities. The final outcome of these activities should be the preparation of a preliminary material assessment report, which gives the justifications and includes the recommended properties used for the design analysis and identify areas of uncertainties and conditions (relevant to the design) where data are instead either missing or unreliable.

#### 4.2 Objectives

The main goals of the activities proposed in this TA should be the preparation of a preliminary material assessment report, which gives the justifications and includes the recommended properties used for the design analysis and identify areas of uncertainties and conditions (relevant to the design) where data are instead either missing or unreliable. An outline proposed for the Material Assessment Report for DEMO conceptual Design Activities is included in the Terms of Reference for the materials studies.

The following activities are proposed:

- Review the current material data or knowledge base for austenitic stainless steels, RAFM – steels (EUROFER), EUROFER ODS (9% Cr), ODS Ferritic steels (12 - 14 Cr), Tungsten and Tungsten alloys, Vanadium and Vanadium alloys, Copper alloys, and SiC/SiC composite relevant for fusion devices beyond ITER.
- Clearly and uniquely define a material (chemical composition, fabrication process, level of development, e.g. industrial available vs. lab scale), in particular:
  - Compile for each of the materials mentioned above, all physical and mechanical data needed for design (for a full list see e.g., Appendix A. Gen of the ITER structural design code). In particular, clearly indicate if measurements techniques deviate from standards (eg ASTM);
  - Indicate and describe fabrication processes and semi - finished products available and limitations in fabrication or machining;
  - Review data from irradiations campaigns, for displacement damage and, as far as possible, He and H /dpa ratio production levels of relevance for DEMO design. In any case clearly indicate the origin of data and irradiation conditions (irradiation source, reactor, spallation etc)
- For each material considered, generate a design space in terms of operating limits (temperature, stress levels, exposure time, life time.). Try to identify areas of safe operation versus areas definitely excluded. [Notes (i) there is no unique approach, it may depend on the material and its relative state of development (ii) in - between safe design space and areas not recommended to be used there is design space where it is up to the choice of the engineer and designer].
  - Identify and clearly describe the key issues and limiting factors and/or properties (e.g. as function of parameters like maximum stress, exposure times, neutron fluence, irradiation temperature.)
  - Identify R&D needs/requirements and define milestones with time period as of 5, 10, 15 years.

- Define a possible experimental and modeling irradiation programme in support of IFMIF, i.e., coherent strategy for material qualification for DEMO complementary to IFMIF and identify potential use of fission reactors, ion beam irradiation stations, EU spallation n - sources; potential exploitation of EVEDA, and the role of modeling.

### **4.3 Work Description and Breakdown**

#### *Structure*

#### *Work Breakdown*

#### **WP11-DAS-MAT-M01**

##### **Assessment of blanket and Divertor design options**

Assessment and discussion of the different design options for Blanket and Divertor concepts (coolant, T-window, structural materials), focusing on design requirements, and mechanical and/or physical properties.

Available resources: 0.05 ppy under Priority Support

#### **WP11-DAS-MAT-M02**

##### **Issues related to radiation on Blanket and Divertor**

Assessment of the issues related to the presence of radiation for Blanket and Divertor materials, focusing on degradation of mechanical and physical properties, He/H production, and design limitations.

Available resources: 0.05 ppy under Priority Support

#### **WP11-DAS-MAT-M03**

##### **Review R&D on materials**

Review of the present status of R&D on materials (in EU and outside of EU), focusing on fabrication, machinability, mechanical and physical properties, and joining techniques. Besides that, a discussion of possible Temperature range of operation (conservative approach and possible margins), key issues and limiting factors should be given.

When lack of information is identified, a list of actions has to be proposed defining milestones for R&D

Austenitic stainless steels (316)

RAFM – steel development (EUROFER)

EUROFER ODS (9% Cr)

ODS steels (12-14 Cr)

Tungsten and Tungsten alloys

Copper alloys

SiC/SiC composite

New concepts: foils, fibre – fibre matrix interphase and matrix, etc.

Available resources: 1.35 ppy under Priority Support

### **WP11-DAS-MAT-M04**

#### **Joining techniques**

Review of the state of art of joining techniques needed in fusion.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-MAT-M05**

#### **Compilation of functional materials information**

Compilation and assessment of the functional materials information, mainly for ceramics and breeders, to identify the current needs in this field and propose a R&D programme.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-MAT-M06**

#### **Possible experiments in IFMIF-EVEDA**

Investigate possible experiments to be carried out using the IFMIF-EVEDA facilities, including a possible time plan.

Available resources: 0.05 ppy under Priority Support

### **WP11-DAS-MAT-M07**

#### **Modelling program for fusion materials**

Compilation and review of the results obtained in the modeling programmes for irradiation damage on fusion materials.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-MAT-M08**

#### **Experiments needed on materials**

Compilation and assessment of needed experiments, which can be carried out with the present facilities, as IFMIF accompanying programme.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-MAT-M09**

### **Fusion materials availability**

Review of the Fusion materials availability.

Available resources: 0.05 ppy under Priority Support

## **WP11-DAS-MAT-M10**

### **Irradiation devices availability**

Review of available irradiation devices, pointing out irradiation time availability, irradiation volume and irradiation conditions

Available resources: 0.05 ppy under Priority Support

### ***JET related activities***

Not applicable.

### ***Resources***

The total resources available is 2.0 PPY under Priority Support.

## **4.4 Scientific and Technical Reports**

### ***Progress reports***

At the end of the Task Agreement during the final monitoring meeting, the task responsible shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

### ***Report of achievements under Priority Support***

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

***Publications***

A list of publications produced on the basis of results of the 2011-WP will be compiled after the completion of these tasks.

***Milestones and Deliverables***

Milestones:

M1 Kick-off meeting

M2 Discretionary review meeting (July - Oct)

M3 Final meeting (Nov - Dec)

Deliverables:

The results of this assessment shall be documented in a comprehensive Material Assessment Report (see tentative outline in [5]).

- An interim report by October 2011.

- A final report by December 2011.

The reports should be accompanied by a clear executive summary including the key findings and recommendations.

***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, *EFDA (11) 47/4.1.1*, 9 March 2011.

[5] Terms of Reference: Review of material database status and needs for DEMO conceptual design activities (ToR\_Materials: EFDA\_D\_2LP3P2)

## 5. Technology/Engineering Issues of Pulsed Tokamak Fusion Reactors:

**Task Agreement WP11-DAS-PLS:**

**Technology/Engineering Issues of Pulsed Tokamak Fusion Reactors**

### 5.1 Introduction

In tokamaks, steady state operation means non-inductive operation where the plasma current is driven by a combination of intrinsic ('bootstrap') current and current externally driven by H&CD systems. The former implies operation at high normalised plasma pressure  $\beta_N$ , challenging the stability limits, the latter implies a large burden on the economic efficiency since the external H&CD system has to be powered by the electrical energy generated by the plant itself. A credible tokamak scenario with very high bootstrap fraction exists on paper, but has not yet been convincingly proven experimentally. We note that this not only requires that the full current is driven non-inductively, but also that the radial profiles of current density and pressure are self-consistently aligned for plasma equilibrium and stability. Hence, this is an area where physics R&D will be needed.

Present-day extrapolations of plasma current drive efficiency in tokamak reactor scenarios, combined with the anticipated poor efficiency of converting wall-plug power into power coupled into the plasma, lead to very large recycled power fractions in steady-state tokamak reactor designs. This problem is exacerbated by the thermodynamic conversion efficiency of the fusion output power, and by the requirement for the large grid demand for the current drive system (if this is significantly larger than the heating power required to achieve ignition or high-Q operation) during start-up of the machine.

The substantial debit on the whole-life cost balance of the machine that steady-state current drive thus engenders could be saved if the reactor was allowed to operate in pulsed mode, but this in turn raises many questions affecting the design of the machine and raising the cost of substantial elements of the structure.

### 5.2 Objectives

This technical review assignment has to address *inter alia* the present state of thinking on likely plasma burn and dwell durations (and hence number of cycles required over a given operational life), thermomechanical creep fatigue in plasma facing components and coolant circuits, the optimisation of reactor load assembly design for the intended number of cycles; high-power, short-duration energy storage systems (on the scale of GW sustained for many minutes), the balance of cost of energy storage against the cost of solenoid recharge power supply requirements, the pros and cons of an AC plasma current design, and superconductor performance degradation with strain and fatigue. More details can be found in the Terms of Reference [6].

## 5.3 Work Description and Breakdown

### *Structure*

### *Work Breakdown*

#### **WP11-DAS-PLS-P01**

##### **Working Group Coordination**

Working Group Coordination, ensuring no overlap with the Working Groups considering materials and plasma heating and current drive.

Available resources: 0.2 ppy under Priority Support

#### **WP11-DAS-PLS-P02**

##### **Review of problems for steady-state DEMO variants**

Review all readily available fusion reactor literature since 1990 and summarise the problems identified in that literature for the steady-state fusion reactor concepts. This should include consideration of extension of present-day heating and current drive systems and plasma-facing components to steady-state applications.

Available resources: 0.15 ppy under Priority Support

#### **WP11-DAS-PLS-P03**

##### **Assessment towards larger solenoid flux swing**

Assess the variation of capital and whole-life costs of a pulsed tokamak version of DEMO with respect to the burn duration, and hence the ability to survive the number of cycles applied to the main load assembly in its lifetime (say 30 years) and to the divertor modules (lifetime say 5 years), recognising the increased cost of the load assembly if it is made to accommodate a larger solenoid flux swing in order to extend the burn duration.

Available resources: 0.2 ppy under Priority Support

#### **WP11-DAS-PLS-P04**

##### **Assess plasma start-up power and energy requirement**

Assess the power and energy requirements needed for plasma initiation, ramp-up to burn and subsequent solenoid recharge in a pulsed tokamak DEMO with unidirectional plasma current, and how these requirements might be met (direct transient grid demand, thermal or electrical or mechanical energy store, or local generator such as gas turbine). Include estimates of the capital and operational costs of each option considered

Available resources: 0.1 ppy under Priority Support

#### **WP11-DAS-PLS-P05**

##### **Investigate present industrial developments in large-scale energy storage systems**

Investigate *commercial off-the-shelf* (COTS) and present industrial development activities in large-scale energy storage systems and show how an energy store with a power capability and capacity sufficient to allow start-up and burn initiation (say  $\sim 300\text{MWe}$  and  $\sim 75\text{MWeh}$ ) could be reliably achieved in DEMO without demanding any power from the grid. Pumped water “mechanical” systems provide examples of COTS solutions that easily meet the requirements, while molten salt thermal energy stores represent up-and-coming systems already built with adequate capacity but so far with very much smaller power capability. For this initial assessment, it should be assumed that “a Pulsed DEMO” should NOT be designed to maintain a constant output to the grid, partly because it should not be designed for a high availability, so inter-shot times are likely to be very long and the energy storage therefore impracticable.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-PLS-P06**

### **Assess relative merits of AC tokamak**

Assess the relative merits of basing a pulsed DEMO concept on an Alternate Current (AC) tokamak. The solenoid current would not then need to be reversed between plasma discharges, greatly reducing the solenoid power supply requirement (which otherwise has to reverse the solenoid current as fast as possible) but problems arise in the divertor and the H-Mode access and ELM behaviour, if either of these is considered necessary in a reactor. The divertor tiles would probably be “imbricated” (i.e. field-line-angle specific) to avoid over-heating the edges, but for bi-directional plasma current would therefore need to be provided with this feature symmetrically, greatly reducing the “wetted fraction” and hence power handling capability. If instead two divertors were provided at opposite ends of the machine, with opposite imbrication and used alternately, then (putting aside the cost of the second divertor) the grad-B drift which affects the tokamak edge physics would be unfavourable for one of them, since it is essentially impossible to keep reversing the toroidal field as well.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-PLS-P07**

### **Optimization of the power required for start-up and burn control versus current drive**

Estimate the plasma heating power required to ramp up to the burn phase (ignition with independently controlled fusion power, or a high-Q scenario with control and sustainment by continuously varied power injection) and optimise the plasma to make use of this plasma heating system for current drive (and hence pulse extension and reduction of the number of cycles required in the reactor life). Include a density variation sufficient to explore efficient current drive (low density) through to efficient exploitation of bootstrap current (high density), ensuring consistency with the ignited or high-Q regime assumed but if necessary allowing the fusion output power to vary.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-PLS-P08**

### **Outline ansatz to indicate variation of cost of reactor load assembly**

Develop an ansatz to indicate the variation of the cost of the reactor load assembly (i.e. the support structures) with the number of tokamak pulses in the assumed calendar lifetime (of say 30 years). This requires the construction of a model structure capturing the key elements of a DEMO design in a fully parameterised way (e.g poloidal location of inter-TF-coil struts, their thickness radially and poloidally, radii where they blend into the TF coil supports, and so on). Subsequently a series of FE analyses is required so that a scaling law of FEA results can be produced which will allow a reactor systems code to optimise the parameters so as to achieve a given number of cycles (or equivalently a given burn duration) with minimal additional cost of the load assembly. Materials data for cyclic fatigue or fracture mechanics predictions are required for the candidate structural alloys, to provide a relationship between the stresses deduced from the scaling law and the permissible number of stress cycles or vice versa.

Available resources: 0.35 ppy under Priority Support

### **WP11-DAS-PLS-P09**

#### **Subroutine for a system code indicating the variation of cost of reactor load assembly**

Develop a sub-routine to include such a parameterised ansatz in a chosen systems code such as PROCESS, and produce graphs of overall whole-life-cost vs number of cycles of assumed life for a selection of candidate structural materials.

Available resources: 0.2 ppy under Priority Support

### **WP11-DAS-PLS-P10**

#### **Review concepts for Nb<sub>3</sub>Sn conductor construction**

Review concepts for Nb<sub>3</sub>Sn conductor construction that do not suffer from any significant strand motion and fatigue due to varying magnetic fields and propose a suitable conductor development and trials programme.

Available resources: 0.2 ppy under Priority Support

### **WP11-DAS-PLS-P11**

#### **Assess cost of better neutron shielding of the superconductor vs cost/problems of nuclear heating**

Assess the cost trade-offs of changing the machine design to reduce significantly (compared to ITER and present outline designs for DEMO in the literature) the total heat load (thermal conduction and radiation, nuclear, eddy-current and motion friction) on the superconducting coils, with respect to the costs and operational problems of tolerating the conductor heating and hence reduced temperature margin for a given superconducting current density and magnetic field strength.

Available resources: 0.3 ppy under Priority Support

#### ***JET related activities***

Not applicable.

### ***Resources***

The total resources available is 2.0 PPY under Priority Support.

## **5.4 Scientific and Technical Reports**

### ***Progress reports***

At the end of the Task Agreement during the final monitoring meeting, the task responsible shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

### ***Report of achievements under Priority Support***

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

### ***Milestones and Deliverables***

Milestones:

M1 Kick-off meeting

M2 Discretionary review meeting (July - Oct)

M3 Final meeting (Nov - Dec) - presentation and review of the results obtained during the analysis of the Technology/Engineering Issues of Steady-State vs. Pulsed Tokamaks.

Deliverables:

The results of this assessment shall be documented in a comprehensive report

- An interim report by October 2011.

- A final report by December 2011.

The reports should be accompanied by a clear executive summary including the key findings and recommendations.

***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, *EFDA (11) 47/4.1.1*, 9 March 2011.

[6] Terms of Reference: Evaluation of the technology/engineering issues of pulsed. vs. steady-state tokamaks for possible applications in future fusion reactors (ToR\_Pulsing: EFDA\_D\_2LP45K)

## **6. Candidate Remote Maintenance Schemes and Solutions:**

### **Task Agreement WP11-DAS-RH:**

#### **Candidate Remote Maintenance Schemes and Solutions**

### **6.1 Introduction**

This Task Agreement describes the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to evaluate the remote maintenance schemes for future Fusion Power Plants (FPPs).

Although the main emphasis is on the maintenance of in-vessel components, work in the future will encompass ex-vessel activities linked to the maintenance of in-vessel components, in particular their transport between the vessel and the hot cell, and ex-vessel maintenance activities proper. The proposed review activities on RAMI and on standardisation should therefore not be limited to in-vessel maintenance operations.

The review in 2011 shall be co-ordinated jointly by a representative from the Associations and a representative from Industry.

### **6.2 Objectives**

The development of remote maintenance schemes for future FPPs shall be driven by the following key requirements: (1) feasibility and reliability of the maintenance schemes, (2) high machine availability, resulting in a maximum duration for the execution of the various maintenance operations and/or the need to carry out several maintenance operations in parallel. This work is particularly crucial because the ITER maintenance scheme for in-vessel components is not reactor-relevant, so that novel maintenance concepts must be developed and validated for use in DEMO.

Although not directly relevant, several important lessons will be learned from RH activities in ITER and in JET. It will therefore be essential to establish and to maintain close links between the persons involved in the DEMO/FPP remote handling activities and their colleagues in JET and in ITER.

More details can be found in the Terms of Reference [7].

### **6.3 Work Description and Breakdown**

#### *Structure*

#### *Work Breakdown*

#### **WP11-DAS-RH-00**

#### **Task Coordination**

Task Coordination

Available resources: 0.4 ppy under Priority Support

## **WP11-DAS-RH-01**

### **Review of the ITER/PPCS divertor maintenance scheme**

Review the ITER/PPCS divertor maintenance scheme to confirm its reactor relevance in 2011. Define the activities to be carried out in this area in 2012-2013.

Available resources: 0.4 ppy under Priority Support

## **WP11-DAS-RH-02**

### **Review of the potential of the banana blanket handling concept**

Review the potential of the “banana” blanket handling concept for DEMO/FPP. Define the activities to be carried out in this area in 2012-2013.

Available resources: 0.4 ppy under Priority Support

## **WP11-DAS-RH-03**

### **Alternative plant architectures**

Consider possible alternative plant architectures which may take into account completely different maintenance schemes (e.g., upper divertor and extraction of blanket segments from the bottom of the machine relying on transfer gallery below ground level, easier draining of components, no huge loads suspended during in-cask etc.), with a view to achieve more effective maintenance schemes. Preliminary work is to be carried out in 2011, to be followed by a more detailed assessment of the proposed schemes in 2012-2013.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-RH-04**

### **Connection of in-vessel components**

Define the design and R&D activities on the connections of in-vessel components (mechanical, hydraulic etc.) to be carried out in 2012 and beyond.

Available resources: 0.1 ppy under Priority Support

## **WP11-DAS-RH-05**

### **Identification of ex-vessel and hot-cell maintenance operations**

Identify the ex-vessel and hot-cell maintenance operations and the logistics aspects to be studied in more detail in 2012-2013.

Available resources: 0.1 ppy under Priority Support.

## **WP11-DAS-RH-06**

### **Preliminary definition of the DEMO port plugs**

Preliminary definition of the DEMO port plugs. Significant differences are expected between the pulsed and the steady-state devices, so that these 2 options ought to be considered separately. This

action is to be carried out in collaboration with other DEMO designers. Identify further work, to be carried out in 2012-2013.

Available resources: 0.2 ppy under Priority Support

### **WP11-DAS-RH-07**

#### **Definition of radiation map in DEMO**

Define the radiation map in DEMO (if possible in 2011) during a plasma pulse and at different points in time after termination of a plasma shot (1hr, 1d, 1w, 1m, 6m). Identify further work to be carried out in 2012-2013 – if appropriate – to refine the radiation map.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-RH-08**

#### **Establishment of RAMI guidelines for all major sub-systems**

Establish RAMI guidelines for all major sub-systems. This activity will be carried out in 2011 and 2012, and a first interaction with experts in the various fields should be foreseen in 2013.

Available resources: 0.1 ppy under Priority Support

### **WP11-DAS-RH-09**

#### **Methodology for the definition of standards**

Define a methodology for the definition of standards. This activity will be carried out in 2011, 2012 and 2013. The work to be carried out in 2012-2013 shall be clarified in 2011.

Available resources: 0.1 ppy under Priority Support

#### ***JET related activities***

Not applicable.

#### ***Resources***

The total resources available will be up to 2.0 ppy under Priority Support.

## **6.4 Scientific and Technical Reports**

#### ***Progress reports***

At the end of the Task Agreement during the final monitoring meeting, the task responsible shall present a report on all activities (under baseline and priority support) under the Task Agreement. These reports shall integrate the progress made by each Association on each activity, and they shall indicate the level of achievement of the objectives, the situation of the activities, the allocation of resources and recommendations for the next year when applicable.

The EURATOM financial contribution will be made through the usual procedures for baseline support through the Contract of Association.

***Report of achievements under Priority Support***

In addition, achievement of Priority Support deliverables will be reported separately to the EFDA Leader. A final report shall be prepared by the Task Coordinator and submitted to the EFDA Leader. Each participating Association will have to report to the Task Coordinator on the degree to which the deliverables of their tasks have been achieved. The Task Coordinator will collect the Associate contributions into the final report for Priority Support activities addressing the associated milestones defined.

The EURATOM financial contribution will be made after approval of these reports by the EFDA Leader.

***Milestones and Deliverables***

Milestones:

M1 Kick-off meeting

M2 Discretionary review meeting (July - Oct)

M3 Final meeting (Nov - Dec)

Deliverables:

The results of this assessment shall be documented in a comprehensive report

- An interim report by October 2011.

- A final report by December 2011.

The reports should be accompanied by a clear executive summary including the key findings and recommendations.

***References***

[1] EFDA 2011 Work Programme Revision 1, Power Plant Physics and Technology activities under EFDA and Dust and Tritium activities, ***EFDA (11) 47/4.1.1***, 9 March 2011.

[7] Terms of Reference: Evaluation of candidate remote maintenance schemes for in-vessel components being proposed for use in future fusion power plants (ToR\_RH: EFDA\_D\_2LCZWW)



[2]

## **REVIEW OF TECHNOLOGICAL MATURITY/DEVELOPMENT NEEDS OF HEATING AND CURRENT DRIVE & FUELLING and PUMPING SYSTEMS FOR DEMO**

### **TERMS OF REFERENCE**

**27.05.2011**

#### **Preamble**

These terms of reference describe the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to evaluate the technological maturity and development needs of Heating & Current Drive and Fuelling & Pumping Systems (the HCD-FP systems) for DEMO.

These ToR were prepared as a result of a number of preparatory meetings involving experts of Associations and Industry and Coordinating Committee Chairs of the Heating and Current Drive and Fuel and Pumping Systems. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

#### **Background**

For the purpose of this assessment and similarly to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degree of extrapolation from the today's known underlying physics and engineering basis if needed should be considered.

- DEMO Model 1: a “conservative baseline design” i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.
- DEMO Model 2: an “optimistic” design, i.e, a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

A preliminary set of technical characteristics and parameters describing these two options is provided in a memo by D. Ward and G. Giruzzi, Proposals for Initial PPPT H&CD Assessments, version 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin.

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

These options provide the plasma parameters required to define the role of the different HCD-FP systems in all phases of the plasma evolution, from creation, to control and to termination of the burning plasma. A second element of the review work is to critically analyze the technology of the HCD-FP systems in terms of the DEMO RAMI requirements. The third and final part of the review work is to produce a well justified roadmap demonstrating the feasibility of the HCD-FP systems in a time frame consistent with the preparation and construction of a DEMO reactor.

### **Foreseen characteristics of the HCD-FP systems for DEMO model 1 and model 2**

#### IC system

For DEMO model 1 the IC system could be in a first approximation a simple extrapolation from the ITER system, meaning that any option must (1) be based upon straps (so  $k// <$  approx 5m-1, or some simple design to work at higher  $k//$ ); (2) use tetrodes; (3) use transmission lines; and (4) have the antenna mounted on a removable plug. The functions of the IC system are: heating, CD (central), burn control (ion heating), ICWC (if required).

For DEMO model 2 two IC systems might be needed, one similar to DEMO 1 tuned for ion heating for heating to H-mode, for burn initiation and for burn control, and a second system tuned for broad profile full CD (but used also in the ramp-up phase) based on high frequency fast wave (HFFW).

#### EC system

The main purposes of the EC system for a DEMO reactor are plasma startup, local current profile control (MHD stabilisation, ITB, ...), bulk heating for access to H-mode and bootstrap control. Recent DEMO studies have lead to the main requirement of a 200 GHz cw source for heating and 220GHz for current drive. Power requirement lies in the range 50 to 100 MW power. To achieve these goals, an improvement of the gyrotron efficiency is required. With the multi-staged depressed collector the system efficiency could approach the 0.6 – 0.7 assumed in the PPCS studies. The benefit from the EC system is the full control of absorption location provided by a real-time multi-beam control of the launchers.

#### LH system

LHCD has been one of the four well proven H&CD systems on tokamaks for years. It is the key element of all the present devices addressing the long pulse issues. In particular, all existing superconducting tokamaks have or plan to have an LHCD system. In ITER, LHCD would be the method:

- to save volt-seconds in the early current ramp-up phase at low beta.
- to extend the plasma duration in the intermediate so-called Hybrid mode of operation.
- to sustain AT steady-state plasmas.

DEMO LHCD system is presently seen as an extrapolation from the ITER system ( $N// \sim 2$ , frequency source of 5GHz) taking into account constraints of nuclear devices. However, and due to the potentially strong damping features of LHCD waves by DEMO plasmas, a detailed scenario study is required: i) assessing the need for CD in DEMO (all phases); ii) setting-up the optimum CD mix.

#### N-NBI system

Negative ion beams are widely used for many different purposes. For a DEMO reactor, it is foreseen to use NBI for plasma heating, CD and q-profile control. Important efforts to increase efficiency concentrate on the understanding of the ion source physics, on the neutralization of the negative ions and on energy recovery systems.

### Fuelling system

Fuelling systems comprise in general gas injection for plasma density control, for supply to neutral beams and diagnostic neutral beams, for injecting impurity gases into the divertor to provide radiative cooling, and for wall conditioning. Pellet injection is used for plasma density control, for ELM control, for enhanced edge radiative cooling and finally for better coupling of the RF injectors with the plasma. Specialized systems comprise injecting impurity gases to mitigate disruptions and for emergency power shutdown. All these systems have to be carefully analysed as they impact on the fuelling throughput and therefore on the pumping system.

### Pumping system

The route towards DEMO is still to develop as there are new technologies who may have the potential to replace the 4K cryopumps. Keeping close to the ITER solution, a helium pumping sorbent working at elevated temperatures has to be developed as could be the case for DEMO model 1. With regard to DEMO model 2, the pumping system has to be looked at from an integral fuel cycle point of view. A continuous high throughput pumping system still need to be developed eventually based on some promising concepts which are on the market such as the cold turbopumps, the diffusion pumping, and membrane foils. Separation of the exhaust gas with the capability for direct internal recycling of the un-burnt fuel is another option for DEMO2 which would result in significant simplification of the fuel cycle.

## **Detailed Review Assignments**

The parameters and technical characteristics of the two DEMO options are listed in the aforementioned document and are expected to be consolidated later this year as part of the system code studies.

A table of content (ToC) of the report has been prepared in advance providing the same structured analysis for all the HCD-FP systems and allowing for a bipartisan reporting. This ToC is organized in three main sections. The relation to the burning plasma is considered first, with a description of the role of the HCD-FP system in the two DEMO options. This section of the report will include a SWOT analysis table to be developed based on factual information (e.g., coupling LH, ICH to H-mode plasma Etc.)

The second part of the ToC calls for a review of the technology involved in the HCD-FP systems making a distinction, whenever possible, between issues which are scenario dependent and those that instead are scenario-independent. The capabilities of the individual components of the systems mainly from the stand point of (mainly) current drive efficiency will be demonstrated through a RAMI analysis. This section defines the core part of the assignments. The physics involved in the major components will be described as well as the state of understanding and numerical code availability.

The third section of the report relates to the identification of the main differences between ITER and the DEMO options from the HCD-FP standpoint and includes a gap analysis and the proposals for PPPT mandatory activities to have the HCD-FP systems ready in time for a DEMO reactor.

The ToC is reproduced at the end of the present document.

### **Breakdown of the work**

The five Coordination Committees (CCIC, CCLH, CCEC, CCNB and CCFP) will provide assistance for the review activities and for the redaction of a final report due at the end of 2011.

### **Ion cyclotron**

#### **IC-1 Coordination of the assessment work and of the physics studies except (HFFWCD) (0.2 ppy PS)**

The coordination of the assessment of the IC system will be managed by the Coordination Committee on Ion Cyclotron. Included in this work package is the review of the physics of IC in DEMO model 1 and 2 based on extrapolation using existing database, ITER design and simple formulas.

For DEMO model 1, the main emphasis of this work package will be given to scenarios 2 fcT in D-T-(3He), ion heating, tails (through a QLFP analysis), CD windows, and frequency range, and includes an assessment of the coupling for an ITER-type antenna (ITER-like scrape-off) and the extrapolation from the CD database.

For DEMO model 2, the objectives are to establish basic physics feasibility of a current drive scheme, assess  $f$  range,  $k_{\parallel}$  requirements, and to provide first estimates of CD efficiency for a limited number of cases.

The study will conclude for the DEMO model 1 case by proposals for refined theoretical investigations and for experiments, in particular for benchmark test of current drive at relevant  $T_e$  on a large tokamak, arc detection and sheath studies. For the DEMO model 2 case, proposals for a longer term program will be made to more accurately describe the high frequency fast wave scheme and on the validation of new launcher concepts.

#### **IC-2 Coordination of the assessment of the technology of IC (0.2 ppy PS)**

The objectives of this work package are to identify suitable power source and transmission system, outline a launcher design and revisit the arc detection and sheath effects, materials to be used and utilities. Part of work will be devoted to define a design and R&D program for building and testing the IC systems.

#### **IC-3 High frequency fast wave current drive (HFFWCD) (0.2 ppy PS)**

The HFFWCD system is considered for DEMO model 2 for broad profile full CD. This work package will develop the physics of the scheme, establish basic physics feasibility, assess  $f$  range,  $k_{\parallel}$  requirements, and provide first estimates of CD efficiency. Also included in this work package is a review of high harmonics FW experiments (on NSTX) and an assessment of their relevance to HFFWCD, an analysis of possible launcher designs and concept and finally the outline of an experimental program.

#### **IC-4 SWOT and preliminary RAMI analysis (0.2 ppy PS)**

This work package is to demonstrate the performance of the IC systems in particular through the SWOT and preliminary RAMI analysis for DEMO model 1 and model 2.

### **Lower hybrid**

#### **LH-1 General coordination and physics analysis (0.1 ppy PS)**

This work package includes the general coordination of the assessment of the LH system.

#### **LH-2 LH Physics analysis (0.2 ppy PS)**

This task calls for a study of DEMO specific physics requirements: scenarios, power coupling, choice of frequency (versus power density, alpha parasitic absorption). This physics analysis task will be consolidated through discussions with the other Coordination Committees. This task includes all activities needed for the SWOT analysis of the LH system.

### **LH-3 Specific technology study (0.2 ppy PS)**

The objective of this activity is to analyse the LHCD specific R&D needs and technology requirements and specifications for nuclear environment: power, source, transmission lines, RF windows, antenna, diagnostics, interfaces, remote handling issues. The study includes a preliminary RAMI analysis and an analysis of LHCD operation in DEMO nuclear environment looking e.g. at full system integration, system monitoring/control/protection, CODAC, and real-time control.

## **Electron cyclotron**

### **EC-1 General coordination and physics analysis (0.2 ppy PS)**

This work package includes the general coordination of the assessment of the EC system. It includes also the study of DEMO specific physics requirements: scenarios, power coupling, choice of frequency. This task also calls for a SWOT analysis of the EC system.

### **EC-2 Technology requirements (0.3 ppy PS)**

The objective of this activity is to analyse the EC specific R&D needs and EC development roadmap, the technology requirements as well as specifications for nuclear environment: power, source, transmission lines, RF windows, antenna, diagnostics, interfaces, remote handling issues. Efficiency of the EC in DEMO will be discussed. The activity includes a preliminary RAMI analysis.

## **Neutral beam**

### **NNBI-1 General coordination and physics analysis (0.2 ppy PS)**

This work package includes, besides the coordination of the assessment of the neutral beam for DEMO model 1 and model 2, an assessment of the heating requirements to drive plasma to burn condition, including dependence on power waveform, an investigation of the current drive sensitivity to beam size and beam energy, power density, position and inclination angle, an assessment of sensitivity to scenario and a SWOT assessment of functionality.

Included in this work package is the Development & Roadmap, based on critical issues, differentiation of the DEMO N-NBI from ITER system and should include recommendations for R&D, priorities, timescales and roadmap

### **NNBI-2 Coordination of the assessment of the technology (0.1 ppy PS):**

The objectives of this work package are to assess the injector configuration and its optimisation (size, inclination angle/beamline length, port number), the shielding (radiation & magnetic), the materials to be used in terms of creep & fatigue and irradiation, the utilities (cooling, cryogenics). Included here is the analysis of the N-NBI in terms of efficiency, and the RAMI and SWOT analysis of technology.

### **NNBI-3 Voltage holding and accelerator (0.1 ppy PS)**

This task calls for an analysis of the voltage holding and accelerator configuration, through a reviewing of the recent modification of the ITER NBI system and linking to the prescription for a DEMO reactor.

### **NNBI-4 Cs management (0.2 ppy PS)**

This work package calls for an assessment of ion sources from the point of view of the physics involved and of geometrical aspects. The Cs management should be emphasized for its direct impact in the preliminary RAMI analysis (e.g. cleaning every year). Status of the code development effort for physics understanding and for ion source management should be included in the study.

### **Fuelling-Pumping**

Fuelling and pumping are treated as individual systems, and a technical support is requested to review the physics involved in the systems. The reporting will follow the common Table of Content. The assessment for DEMO 1 requires an in-depth knowledge of the design and physics behind the ITER systems, in order to derive a proper assessment of the maturity (under RAMI aspects) and extrapolability of these systems towards DEMO.

As there are various technological FP concepts under consideration for DEMO 2, the assessment shall be performed for each of these based on the method of pairwise comparison. This assessment shall form the basis for the SWOT and the RAMI analysis.

### **F-1 General coordination (0.2 ppy PS)**

Besides the general coordination of the assessment of the Fuelling systems, the work package calls for a SWOT and preliminary RAMI analysis and for a roadmap of developments of fuelling systems for DEMO model 1 and DEMO model 2.

### **F-2 Physics aspects of DEMO fuelling (0.2 ppy PS)**

This work package calls for an analysis of the physics knowledge in the area of fuelling in particular for DEMO model 1 and model 2 conditions. The objectives of this activity are to identify efficient core and edge fuelling methods and their impact on a reactor design (poloidal and toroidal distributions; magnetic connection) and to test whenever possible their scaling up from ITER. The work includes an analysis of the status of code development needs.

### **P-1 General coordination (0.1 ppy PS)**

The assessment of the pumping systems will use the method of pairwise comparison to come to unbiased results and link this with the SWOT approach. Some input are however lacking to scale the physics parameter to a throughput. Therefore the analysis will be given for a range of acceptable values only. Also important is the divertor and the achievable neutral pressures in its area whose impact on the pumping will be analyzed. The work package also calls for a roadmap for the development of pumping systems for DEMO.

### **P-2 Assessment of physics code for determining the pumping capabilities (0.2 ppy PS)**

Extrapolation of the pumping system from ITER to DEMO will be difficult. Therefore tools such as numerical codes are needed to understand physics issues linked to the divertor and pumping geometries. This work package calls for an analysis of the needs in code development, and experimental testing for an integrated pumping system design in DEMO. The work package also calls for an analysis of the role of the pumping system in controlling the plasma performance.

### **Available Technical Documentation**

- David Ward and Gerardo Giruzzi; "Proposals for Initial PPPT H&CD Assessments" containing a list of H&CD Starting parameters for analysis of DEMO Option 1 and 2.
- G. Giruzzi, J. Garcia : CCEC Meeting Cadarache Feb. 2010 + DEMO Session EC16 April 2010
- Final Report of the European Fusion Power Plant Conceptual Study (PPCS) April 2005 : EFDA-RP-RE-5.0
- L.D. Horton : US/Japan Workshop on Power Plant Studies Jan. 2006

- HCD mix for ITER: WP08-09-HCD-02FR-PS CEA 10 x.pdf
- Wagner report AG-2report final.pdf

**Deliverables/ schedule**

This activity is expected to last for 4-6 month. The results of this assessment will be documented in a comprehensive report to be submitted with an executive summary including the key findings and recommendations.

**Milestones**

M1 - Kick of Meeting to organize the work

M2 - Interim Progress Meeting to assess the status of the work and provide guidance for integration of the studies

M3 - Final meeting

**Structure of the assessment report**

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Systems

- 1 Neutral beam system
- 2 Lower hybrid system
- 3 Electron cyclotron system
- 4 Ion cyclotron system
- 5 Fuelling system
- 6 Pumping system

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- SYSTEM
- 1 INTRODUCTION
- 2 FUNCTION
- 3 REQUIREMENTS
  - . DEMO Model 1
  - . Scenario dependency
  - . SWOT
  - . Efficiency
  - . DEMO Model 2
  - . Scenario dependency
  - . SWOT
  - . Efficiency
- 4 DESIGN ISSUES REFERENCE SYSTEM - DEMO Model 1
  - . Configuration
  - . Ports
  - . Sources
  - . ...
  - . ...
  - . Magnetic shielding
  - . Nuclear shielding
  - . Materials
  - . Utilities
  - . RAMI
  - . Efficiency
  - . Critical issues
  - . Future developments

. Recommendations  
5 DESIGN ISSUES ALTERNATE SYSTEM - DEMO Model 2  
. Configuration  
. Ports  
. Sources  
. ...  
. ...  
. Magnetic shielding  
. Nuclear shielding  
. Materials  
. Utilities  
. RAMI  
. Critical issues  
. Future developments  
. Recommendations  
6 CONCLUSIONS

[3]

**EVALUATION OF THE STATUS AND PROSPECTS OF  
HIGH TEMPERATURE SUPERCONDUCTING (HTS) MAGNETS  
FOR POSSIBLE POTENTIAL APPLICATIONS IN FUTURE FUSION REACTORS**

**TERMS OF REFERENCE**

**30.5.2011**

**Preamble**

These terms of reference describes the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 on high temperature superconducting (HTS) magnets to determine status and prospects of design and R&D activities for possible potential applications in future fusion reactors.

These ToR were prepared as a result of a preparatory meeting involving experts of Associations and Industry that was held at EFDA CSU Garching on May 10-11, 2011. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

**Background**

Low temperature superconducting magnet technology is being used in ITER and it has been considered as reference for previous EU fusion reactor studies (e.g., PPCS). Currently, superconducting magnets are designed with large safety margins because of incomplete understanding of their properties. For example, existing codes cannot self-consistently predict distribution of strains and electrical current in superconducting cable. Also lacking is the ability to predict crack growth and damage in composite materials. Large safety margins are also needed because the lack of adequate quench detection diagnostics requires very conservative magnet protection designs. Nuclear effects including heating in the conductor and damage to thermal and electrical insulators have not been fully characterized. However, degradation is observed in some samples after mechanical load cycling and e.g. for ITER TF coils the safety margin in the high field area is approx. 1 K, only.

High-temperature superconductors (HTS) have the potential to enable operation at higher magnetic field (> 14T) at-much higher temperature (up to 50 K) in the fusion geometry than conventional superconductors.

Recent developments show promises that novel high temperature superconductors may become available with high critical currents and magnetic field capabilities as required for fusion applications. In the largest part this research is beyond the scope of the fusion programme and still in the fundamental phase requiring significant research before it can be employed reliably in fusion devices. For example, in high-temperature superconductors, quench propagation slows about three orders of magnitude from 10m/s to 10mm/s, requiring development and integration of new techniques for quench detection. On the other hand using magnets at temperature > 50 K could allow omitting the LN2 thermal shield saving significantly cooling power and improving availability which would increase the performance of a future fusion reactor significantly and simplifies the machine.

As a consequence a program should be implemented with a breadth that ensures information and technology flow to allow the application of these promising technologies at the earliest useful moment.

The potential and the benefits of high temperature HTS magnet technology have been preliminary investigated and technical information is described in the references below.

In line with the overall focus of the design activity, the main scope of this assessment will address integration aspects.

In particular, enabling operation at high magnetic fields with good temperature tolerance is perceived to be an important advantage in a DEMO reactor especially to compensate/mitigate potential performance shortfall risks that may arise from the fact that reliable operating scenario at high density (i.e.,  $n > n_G$  - Greenwald limit) could be difficult to be established, and this in the absence of compensating measure with coil design that operate at high fields would translate into the inability to achieve significant level of fusion power in a reactor.

For the purpose of this assessment and similarly to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degree of extrapolation from the today's known underlying physics and engineering basis if needed should be considered.

- DEMO Model 1: a “conservative baseline design” i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.
- DEMO Model 2: an “optimistic” design, i.e. a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

A preliminary set of technical characteristics and parameters describing these two options is provided in a memo by D. Ward and G. Giruzzi, Proposal of Preliminary Machine Parameters for Initial Assessments, version 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters.

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

### **Available Technical Documentation**

The technical documentation available of the subject is:

- [1] I. Cook, D. Maisonnier et al., European Fusion Power Plant Studies, TOFE conference, 2004

- [2] D. Maisonnier et al., DEMO and fusion power plant conceptual studies in Europe, *Fusion Engineering and Design* 81 (2006) 1123–1130
- [3] I. R. Dixon et al., Current Sharing and AC Loss Measurements of a Cable-in-Conduit Conductor with Nb<sub>3</sub>Sn Strands for the High Field Section of the Series-Connected Hybrid Outsert Coil; Proceedings of the Applied Superconductivity Conference, ASC 2008, Chicago USA, Aug. 17-22, 2008
- [4] D.W. Hazelton et al., Recent Developments in 2G HTS Coil Technology, Proceedings of the Applied Superconductivity Conference, ASC 2008, Chicago USA, Aug. 17-22, 2008
- [5] V. Selvamanickam et al., High Performance 2G Wire: From R&D to Pilotscale Manufacturing; Proceedings of the Applied Superconductivity Conference, ASC 2008, Chicago USA, Aug. 17-22, 2008
- [6] D.C. Larbalestier et al., Strongly linked current flow in polycrystalline forms of the superconductor MgB<sub>2</sub>, *Nature* 410 (2001) 186-189
- [7] K. Vinod et al., Prospects for MgB<sub>2</sub> superconductors for magnet application; *Supercond. Sci. Technol.* 20 (2007) R1–R13
- [8] A. Portone et al, Design and procurement of the EDIPO superconducting magnet, *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY*, VOL. 18, NO. 2, JUNE 2008, 499-504
- [9] J.L. Duchateau, P. Hertout “Which superconducting material for the toroidal field system of the fusion DEMO reactor?” 2008 *J. Phys.: Conf. Ser.* 97 012038
- [10] EFDA Task HTSMAG (2005 working programme)
- [11] W.H. Fietz, R. Heller, S.I. Schlachter, W. Goldacker, Application of high temperature superconductors for fusion, *Fusion Eng. Des.* (2010), in press <http://dx.doi.org/10.1016/j.fusengdes.2010.11.018>

## Detailed Review Assignment

For Fusion application in a DEMO reactor two promising superconductor materials have been discussed as candidates: the high temperature superconductor REBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> (RE-123) which can operate at the required field ( $\approx 14$  T) at  $T > 50$  K (reducing costs on the cryogenic system and on the LN<sub>2</sub> shielding) and the low temperature superconductor MgB<sub>2</sub> since it has some potential to relax the cryogenic requirements ( $< 20$  K) being a relatively cheap alternative to NbTi and already on the market used for MRI applications, for instance.

There are a set of particular issues related to the development of HTS for fusion application that need to be investigated and for which a feedback loop and/or a partnership with industry is highly desirable.

### Table of specific tasks

The following activities are proposed with the aim to

- review of various solutions investigated in the past
- identify the potential of these options, and the associated development issues, to operate at high fields
- provide recommendations for further research to be carried out distinguishing from small scale lab test to medium scale prototype test
- identify areas where industry should be involved
- provide a tentative roadmap with estimate of resources needed

### Work Breakdown

HTS, in particular RE-123 coated conductors, represent a highly promising option for the operation of fusion magnets at elevated temperatures or at higher fields. As a first task an assessment shall clarify the needs for a 3 years program, targeting a scalable high field, high current HTS fusion conductor. After this period it has to be checked if a promising scalable cable solution has been found that can be used in a second 3 years period to demonstrate the feasibility of this conductor type for high current, high field fusion coils.

To clarify the necessary work of the associations in the first three years period, the following proposals for assessment are made:

#### Subtask 1

Coordination of Task

#### Subtask 2

- HTS Material survey and usability for fusion
  - RE-123 B<sub>max@conductor</sub> for 50 K, 27 K, 4.5 K
  - Bi2212 high field option at  $T < 20$  K?
  - Bi2223 high field option at  $T < 20$  K?
  - MgB<sub>2</sub> as a NbTi replacement?
- Scalable cabling concepts for currents in the tens kA range ( $> 20$  kA)
  - Scalable cabling designs in literature
  - Solutions that industry is investigating
  - Possible industrial application on this type of cables
- Mechanical strength to withstand electromagnetic forces
  - Influence of mechanical forces on HTS cable configurations
  - Used cable configurations by industry - what are their operation ranges;
  - Are the available solutions useful for fusion requirements (several kA under fields of 7-14T)?
  - What is the existing industrial experience with properties of single tapes and cables as a basis for the mechanical reinforcement of HTS conductors?

- Cooling requirement and concepts
- Demonstration of scalable cabling concepts
- Roadmap towards a HTS fusion magnet
- List of necessary resources for this work
- Time schedule for this work

### Subtask 3

To use RE-123 in fusion magnets, following aspects should be assessed:

- Influence of fast neutron irradiation on the performance of RE-123 coated conductors.  
The following issues need to be addressed:
  - Change of  $T_c$  with neutron fluence in the ITER / DEMO fluence range ( $1 \times 10^{22} \text{ m}^{-2}$  and beyond).
  - Change of  $J_c$  with neutron fluence in the temperature range from 50 to 77 K.
  - Change of the angular dependence of  $J_c$  with neutron fluence.
  - Change of ac losses with neutron fluence.
  - Change of the strain tolerance with neutron fluence.
- Update of the corresponding data base on radiation effects on commercial coated conductor tapes, initiated in the framework of the EFDA Task HTSPER.
- Comparison of results with data on  $\text{Nb}_3\text{Sn}$ .
- Evaluate the needs of current accelerator designs (e.g. LHC Upgrade).
- Assess the homogeneity of current flow in coated conductor tapes and cables by trapped field scanning and by magnetoscan.
- Assess the need of replacing Y by another RE in order to reach the field and temperature requirements of fusion magnets.
- List of necessary resources for this work
- Time schedule for this work

### Subtask 4

For the future use of RE-123 in fusion magnets, the assessment of following aspects is necessary:

- Definition of appropriate combinations of operating current, temperature, and field.
- Option for relatively high field in connection with operation temperatures of 4.5 K and 27 K (cooling by neon possible)
- Electrical stabilization
- Quench protection
- Possibility of conventional quench protection in a winding forced-flow-cooled by helium gas?
- Characterization of full size samples and small insert coils
- Test of straight HTS samples ( $I > 10 \text{ kA}$ ,  $B > 10 \text{ T}$ ) (possible adaptation of the SULTAN test facility)

In addition:

- Compare the performance and the cost of industrially fabricated  $\text{MgB}_2$  wires with those of  $\text{NbTi}$ .
- Material survey and usability for fusion
  - RE-123  $B_{\text{max@conductor}}$  for 50 K, 27 K, 4.5 K
  - Bi2212 high field option at  $T < 20 \text{ K}$ ?
  - Bi2223 high field option at  $T < 20 \text{ K}$ ?
  - $\text{MgB}_2$  as a  $\text{NbTi}$  replacement?
- Experimental comparison of MQE and NZP for different wire designs
- List of necessary resources for this RE-123 work and additional work
- Time schedule for RE-123 work and additional work

### Subtask 5

Assessment for RE-123 fusion cable joints is necessary in the fields:

- Review the state of the art of the joint solutions for ReBCO cable

- Joint fabrication trials
- Solutions industry is adopting to join conductors?
- Are these industry solutions scalable for fusion application
- Modelling of joint concept in optimising heat load for DC transport current and AC applied field variations and DC non-uniform current distribution
- List of necessary resources for this work
- Time schedule for this work

### Subtask 6

An assessment for a RE-123 fusion cable with low ac losses is necessary in the fields:

- Acceptable loss (W/m) for HTS and comparison to LTS for  $f < 10$  Hz incl. consequences for possible cable layouts.
- AC loss in scalable RE-123 cables incl. Roebel cables – theory and modelling for frequencies  $< 10$  Hz
- AC loss in scalable RE-123 cables incl. Roebel cables – manufacturing and experiments for frequencies  $< 10$  Hz
- AC loss optimization and characterization- responses to several per cent current variations (kA) below 10 Hz under self fields of 7-14T.
- AC loss optimization and characterization- responses to external field variations below 10 Hz. What industrial solutions exists and for what applications?
- What industrial solutions exists and for what applications?
- Reference testing conditions for ac loss determination in HTS cables
- Numerical methods for ac loss estimation in magnetic systems from HTS cables
- Coupling loss and DC non-uniform current distribution modeling aiming for optimal stability
- List of necessary resources for this work
- Time schedule for this work

### Subtask 7

To avoid negative influence of strain effects on a possible RE-123 high field, high current cable, following aspects should be assessed:

- Strain effects on strands, cable & conductor
  - Transport properties and strain load in tapes and various cable layouts suitable for high current cable concept
  - Influence of transverse and axial load on the transport properties of cabled conductors under magnet operating conditions down to 4 K.
  - Transport properties of wires under periodic bending, spatial (periodic point contact) and homogeneous transverse load, axial tensile and compressive strain incl. ac losses and interstrand contact resistances with varying B and T
  - Ability for current redistribution for locally varying strain and crack growth on the critical current
  - List of necessary resources for this work
  - Time schedule for this work

The work breakdown including ppy is given in Table 1.

	Activities	Priority Support (ppy)
Subtask 1	Task Coordination	0.20

Subtask 2	<p>Assessment of HTS material, scalable cabling concepts incl. demonstration, mechanical cable strength and cooling concepts</p> <ul style="list-style-type: none"> <li>• HTS material survey and usability for fusion</li> <li>• Scalable cabling concepts for currents in the tens kA range (&gt;20kA)</li> <li>• Mechanical strength to withstand electromagnetic forces</li> <li>• Cooling requirement and concepts</li> <li>• Demonstration of scalable cabling concepts</li> <li>• Resource and schedule definition</li> </ul>	0.70
Subtask 3	<p>Assessment of influence of fast neutron irradiation on RE-123 material incl. check of homogeneity of current flow in coated conductor</p> <ul style="list-style-type: none"> <li>• Influence of fast neutron irradiation on the performance of RE-123 coated conductors incl. update of the corresponding data base</li> <li>• Comparison to results with Nb3Sn</li> <li>• Assess the need of replacing Y by another rare earth element (RE)</li> <li>• Assess the homogeneity of current flow in coated conductor tapes and cables</li> <li>• Resource and schedule definition</li> </ul>	0.20
Subtask 4	<p>Assessment of electrical stabilization, quench protection incl. He-gas cooled cable designs and characterization of full size samples &amp; small insert coils incl. test of straight HTS samples</p> <ul style="list-style-type: none"> <li>• Definition of appropriate combinations of operating current, temperature, and field (aiming at operation field &gt; 14T)</li> <li>• Option for relatively high field in connection with operation temperatures of 4.5 K and 27 K (cooling by neon possible)</li> <li>• Electrical stabilization</li> <li>• Quench protection incl. He-gas cooled cable designs</li> <li>• Characterization of full size samples and small insert coils incl. test of straight HTS samples (<math>I &gt; 10</math> kA, <math>B &gt; 10</math> T)</li> <li>• Resource and schedule definition</li> <li>• Compare performance and cost of industrially fabricated MgB<sub>2</sub> wires with NbTi.</li> <li>• HTS material survey and usability for fusion</li> <li>• Resource and schedule definition</li> </ul>	0.30
Subtask 5	<p>Assessment for RE-123 fusion cable joints</p> <ul style="list-style-type: none"> <li>• Review the state of the art of the joint solutions for REBCO cable</li> <li>• Joint fabrication trials</li> <li>• Industry solutions to join HTS conductors and possibilities to scale for fusion application</li> <li>• Modelling of joint concept in optimising heat load</li> <li>• Compare the performance and the cost of industrially fabricated</li> <li>• Resource and schedule definition</li> </ul>	0.20
Subtask 6	<p>Assessment of RE-123 fusion cable with low ac losses</p> <ul style="list-style-type: none"> <li>• AC loss in scalable RE-123 cables incl. Roebel cables – theory, modelling, manufacturing and experiments for frequencies &lt;10 Hz</li> <li>• AC loss optimization and characterization- responses to external field variations or several per cent current variations (kA) below 10 Hz.</li> <li>• Reference testing conditions for ac loss determination in HTS cables</li> <li>• Numerical methods for ac loss estimation incl. coupling loss and DC non-uniform current distribution modeling Resource and schedule definition</li> <li>• Resource and schedule definition</li> </ul>	0.20
Subtask 7	<p>Assessment of strain effects on a possible RE-123 high field, high current cable</p> <ul style="list-style-type: none"> <li>• Transport properties and strain load in wires and various cable layouts</li> </ul>	0.20

	<ul style="list-style-type: none"> <li>• Influence of transverse and axial load on transport properties under operating conditions</li> <li>• Transport properties of wires under periodic bending, spatial (periodic point contact) and homogeneous transverse load, axial tensile and compressive strain</li> <li>• Tensile stress-strain characterization and crack analysis (SEM) of wires and cables</li> <li>• Experimental study of mechanical properties of cabled structures under cyclic transverse and axial load</li> <li>• Intrastrand resistance measurement</li> <li>• Resource and schedule definition</li> </ul>	
<b>Total</b>		<b>2.00</b>

### **Deliverables/ schedule**

This activity is expected to last for 4-6 month. The results of this assessment will be documented in a comprehensive report to be submitted with an executive summary including the key findings and recommendations.

[4]

**EVALUATION OF CURRENT CONCEPTUAL SOLUTIONS FOR DEMO DIVERTOR  
AND BREEDING BLANKET INCLUDING AN ASSESSMENT OF THE COOLANTS  
FOR IN-VESSEL COMPONENTS**

**TERMS OF REFERENCE**

**27.5.2011**

**Preamble**

These terms of reference describes the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to determine status and prospects of design concepts and R&D needs of in-vessel components associated in particular with the selection of coolants.

These ToR were prepared as a result of a preparatory meeting involving experts of Associations and Industry that was held at EFDA CSU Garching on May 10-11, 2011. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

**Background**

To enhance the efficiency of the energy production within DEMO, there is a need to utilise coolants for the blanket and divertor that may sustain elevated operating temperatures. However, the selection of a suitable coolant is made difficult by the number of many factors that must be considered, such as thermal and radiation stability, required pumping power, compatibility with structural materials, coolant availability, economics.

Although alternative coolants are being considered, the most credible options for DEMO are helium and water. The two options have been considered in the PPCS study regarding the liquid breeder [1,4] The development of high temperature He-cooling technologies is very demanding. While non-fusion specific technologies (pressurization and He circulation) might be developed for fission projects, some fusion specific R&D issues need to be addressed [5]. In particular He-cooled in-vessel components, such as the He-cooled W-divertor project has been pursued at KIT [6] and ENEA [7]. It is however far from certain that He-related R&D will be successfully completed in time for DEMO. Water-cooled divertor concepts have been developed allowing maximum incident fluxes up to 15 -20 MW/m<sup>2</sup> [8,9]. However, the behaviour under irradiation of some considered materials (CuCrZr, Graphite, ...) is questionable. and a water-cooled divertor concept which uses steel (e.g., EUROFER) as a heat sink material and W as armour is limited to a much lower maximum incident flux. Nevertheless, It would be appropriate to consider the credibility of possible back-up options, i.e. a water cooled DEMO, and the required R&D. The main concern in this case is the

EUROFER embrittlement at around 300°C [10] and the safety concerns related to the water–LiPb reaction in case of accident [11].

Finally, while there would be significant benefits in operating DEMO and reactors at relatively high first-wall temperatures (in the range 300–500 °C, depending on the cooling options He or water), it should be pointed out that first wall temperatures in all tokamaks presently operating or foreseen (including ITER) are in the range 200–300°C. No foreseen device will therefore provide demonstration of in-vessel operation in DEMO relevant ranges of plasma facing component temperatures. This is a significant gap in the fusion programme worldwide, which needs to be filled.

Work done in the past showed that if the coolant selected is helium, the process is not presently industrially qualified. It was assumed in the past that this technology was going to be developed mainly by non-fusion applications (e.g. high temperature helium-cooled Generation IV fission reactors) or that adequate funds are made available for this purpose within the fusion development budget.

In addition to the cooling of the in-vessel components, it is usually assumed that the components of the balance of plant (the cooling and power conversion systems in particular) do not require any development. This would be true for a water cooled DEMO with water at PWR conditions (325°C, 155bar) as there are hundreds of PWR's in operation. For a helium-cooled DEMO, key equipments for the primary heat transfer system and for the power conversion system do not exist, they must be developed (heat exchangers, blowers, turbo-generators, etc.). Either these developments are undertaken by another community, e.g. Gen. IV fission reactors, or the fusion community should assess whether it could support these developments on its own. The resources required would be considerable and the availability of these systems could be a major concern. It is worth recalling that, in the 70's, the major causes of PWR's unavailability were BoP components and systems.

For the purpose of this assessment and similarly to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degree of extrapolation from the today's known underlying physics and engineering basis if needed should be considered.

- DEMO Model 1: a “conservative baseline design” i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.
- DEMO Model 2: an “optimistic” design, i.e. a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

A preliminary set of technical characteristics and parameters describing these two options is provided in a memo by D. Ward and G. Giruzzi, Proposal of

Preliminary Machine Parameters for Initial Assessments, version 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters.

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

### **Available Technical Documentation**

- [1] D. Maisonnier, et al., Power plant conceptual studies in Europe, Nucl. Fusion 47 (2007) 1524–1532.
- [2] D. Maisonnier, et al., the European Power plant conceptual study, Power plant conceptual studies in Europe, Fusion Engineering and Design 75-79 (2005) 1173–1179.
- [3] P. Sardain et al., The European Power Plant Conceptual Study: Helium-Cooled Lithium Lead Reactor Concept, Fusion Engineering and Design 81 (2006) 2673 - 2678
- [4] P. Sardain et al., Power Plant Conceptual Study – WCLL concept, Fusion Engineering and Design 69 (2003) 769 – 774
- [5] M. Medrano et al., Power conversion cycles study for He-cooled reactor concepts for DEMO, Fusion Engineering and Design 82 (2007) 2689–2695
- [6] P. Norajitra et al., Divertor Conceptual Designs for a Fusion Power Plant, Fusion Engineering and Design 83 (2008) 893–902
- [7] A. Pizzuto et al., HETS performances in helium-cooled power plant divertor, Fusion Engineering and Design 75-79 (2005) 481–484
- [8] L. Giancarli et al., Conceptual design of a high temperature water cooled divertor, Fusion Engineering and Design 75-79 (2005) 383–386
- [9] A. Li Puma et al., Optimization of a water-cooled divertor for the European PPCS, Fusion Engineering and Design 61-62 (2002) 177–183
- [10] Bob van der Schaaf, C. Petersen, Y. de Carlan, J.W. Rensman, E. Gaganidze, X. Averty et al., High dose, up to 80 dpa, mechanical properties of Eurofer 97, J. Nucl. Mater. (2009), available online, doi:10.1016/j.jnucmat.2008.12.32
- [11] P. Sardain et al., Modelling of the lithium-lead/water interaction within a blanket module, Fusion Engineering and Design 51-52 (2000) 611-616

## Table of specific tasks

The analyses will take into account work done in the past in this area (see references above) and review the technical solutions that have been proposed.

IVCC1	Working Group Coordination, ensuring no overlap with the Working Groups considering materials and Issues of Pulses Device and Activity on a Feasibility study of a water-cooled divertor for DEMO based on the optimisation of the ITER W-monoblock design and technology the on covered in 2011 by another call (CfP-WP11-PEX-01)].	0.2
IVCC2	Review what can be gained from ITER regarding the blanket concepts; analyse the DEMO relevancy of the Test blanket Modules to be implemented in ITER. Conduct a risk analysis, by identifying the main risks and impacts and conducting a risk mitigation strategy.	0.2
IVCC3	Carry out a literature review to determine the availability of helium supplies in the future.	0.2
IVCC4	Review the current status and perspectives of the development of the helium systems, in particular in the frame of Generation IV. Identify possible development synergies with the fission area.	0.2
IVCC5	Identify the issues identified during past studies regarding water-cooled blanket concepts. Review the rationale and technology development considerations that have led to the exclusion of water-cooled blanket options for DEMO.	0.2
IVCC6	Revisit the rationale and technology development assumptions that have led to the selection of current He-cooled blanket design concepts. Identify main R&D issues and elaborate a provisional roadmap for possible realistic developments in the various areas, with an estimate of the resources needed.	0.2
IVCC7	Perform a risk analysis for the possible blanket concepts for DEMO Model 1 and Model 2, based on technological aspects. Establish a risk register.	0.2
IVCC8	Review the water-cooled divertor concepts studied in the past, giving the performance limitations related to the various heat sink and structural materials <i>[It should be noted that a specific task focussing on an ITER-like technology is defined in another call (CfP-WP11-PEX-01)].</i>	0.3
IVCC9	Review status and perspectives of the development of the helium-cooled divertor. Identify main R&D issues, performance limitations and elaborate a provisional roadmap for possible developments with an estimate of the resources needed.	0.1

IVCC10 Perform a risk analysis for the possible divertor concepts for DEMO Model 1 and Model 2, based on technological aspects. Establish a risk register. 0.2

### **Resources**

Total: 2 PPY

### **Deliverables/ schedule**

This activity is expected to last for 4-6 month. The results of this assessment will be documented in a comprehensive report to be submitted with an executive summary including the key findings and recommendations.

[5]

## REVIEW OF MATERIAL DATABASE STATUS AND NEEDS FOR DEMO CONCEPTUAL DESIGN ACTIVITIES

### TERMS OF REFERENCE

**27.5.2011**

#### **Preamble**

These terms of reference describe the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to review the material database status and need for DEMO Conceptual Design Activities.status.

These ToR were prepared as a result of a number of preparatory meetings that took place during the last two months, involving experts of materials and the Chairmen of relevant EFDA Topical Groups. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

One of the main goals of these activities should be the preparation of a preliminary material assessment report, which gives the justifications and includes the recommended properties used for the design analysis and identify areas of uncertainties and conditions (relevant to the design) where data are instead either missing or unreliable.

#### **Background**

The unique combination of intense and highly spatially heterogeneous high-energy neutron fluxes, the expected high and spatially unevenly distributed accumulated radiation dose, high heat fluxes, tritium production, high temperature coolants, and the need to combine several types of materials within an integrated engineering structure poses immense challenges to the materials that constitute the in-vessel components in a fusion device.

In the 1990s, the need to establish a viable ITER engineering design stimulated important applied and fundamental materials R&D activities. Research topics stimulated by ITER included low temperature radiation hardening and flow localization issues (including dislocation channeling), structural joining of dissimilar metals (Cu/stainless steel, W/Cu, etc.), effects of alternative stainless steel processing methods (hot isostatic pressing, casting, etc.) on the properties and irradiation response, plasma facing materials redeposition processes and high heat flux technologies, and the mechanical properties of high-strength, high-conductivity copper alloy in their unirradiated and irradiated condition. The ITER project also stimulated considerable activities on improved engineering design criteria for structural materials, particularly for cases where neutron irradiation may produce low uniform elongations.

The selection of materials for ITER was based on a total engineering approach. This balances physical and mechanical properties, radiation effects, processing capabilities, joining, maintainability, reliability, and waste disposal considerations. A specialized formulation of austenitic stainless steel that falls within the category of Type 316L(N) was selected as the

primary structural material for ITER, based on industrial capabilities to manufacture the necessary complex components and an extensive data base (unirradiated and irradiated) and design equations based on ASME and RCC-MR code requirements. Several different materials were extensively evaluated for plasma erosion protection, including beryllium for first wall and limiter, tungsten for divertor components, and carbon fiber reinforced carbon composites for the vertical target. Two types of copper alloys (oxide dispersion strengthened Cu-Al<sub>2</sub>O<sub>3</sub> and CuCrZr) were selected from a wide range of initial candidate materials for first wall and divertor high heat flux heat sink substrate materials.

The structural, heat-sink and protection materials that are being used for the fabrication of the ITER in-vessel components are considered to be not suitable for the fabrication of the plasma facing components of a Demonstration Fusion Reactor (DEMO). Irradiation by high energy neutron causes considerable damage to the materials surrounding the plasma. The damage, where dpa (displacement per atom) is commonly used as a meaningful metric is expected to be two orders of magnitude higher in DEMO than in ITER. In particular, but not exclusively the first 10-20 cm region surrounding the plasma, the severe irradiation conditions will lead to significant degradation of physical and mechanical properties. In addition, the need to use high temperature coolants in the blanket region, to improve thermal efficiency of the heat exchange process, requires structural material with overall good mechanical properties in an as large as possible temperature window. Efforts during the last 10-20 years has been mainly oriented towards developing radiation-resistant materials, capable to operate at temperatures corresponding to gas cooled blanket options (e.g., mainly, Ferritic - Martensitic steels such as EUROFER, ODS EUROFER steels, Ferritic ODS steels). Component life and performance limits depend from a multi-parameter field eg of temperature, loads applied and loading history resulting in requirements on a long list of material properties.

A measure on technical readiness of concepts has to take into account material properties as part of specific design. Today, for the materials and concepts under development some or even many properties are below requirements. This could be in terms of insufficient temperature-window or brittleness or strength or thermal conductivity, to mention some of the most prominent risk factors.

In addition, the major uncertainties are due to the very specific fusion environment that cannot be easily investigated or simulated elsewhere. Issues like changes in the microstructure of the materials, which controls the actual degradation of the physical and mechanical properties, depend to a large extent on the amount of gaseous transmutations, He and H, produced, under neutron irradiation, which are one or two order, or sometimes many orders of magnitude higher than under fission conditions. Other issues and uncertainties are due to fabrication processes and scalability of them, joining technologies where many of them had and have to be newly developed and never before were used in a nuclear facility.

In conclusion, selecting candidate of reference materials for design of DEMO in vessel components is facing often one or more of the following difficulties: the materials and respective fabrication and joining technologies are not yet developed or not yet available at industrial scale or the material data base is insufficient or combinations of materials (materials systems) are not explored.

In order to review the status and to foster most urgent R&D needs, it is necessary to carry out for all candidate materials a critical assessment, taking into account their application in an integrated and iterative material-design approach as well as increased knowledge obtained by the international fusion community in the last decade in this field, which come, in particular from large and extended irradiation campaigns. It furthermore requires measures for technological readiness of the materials with respect to their anticipated use in the design of the next fusion facility.

A precondition to any design process is to have available a materials data base and design methodologies and design allowable data. The material should be from the beginning as complete and comprehensive as possible. In the early stages of a system design process, candidate materials could then be identified based on their specific functionality. Design space is defined and limited by requirements such as geometry, operation conditions (loads, temperatures) and materials properties. Engineering design and progressing detailed analyses requires more data (which might initially not be available) or data at higher level of confidence, thus initiating new characterization and validation programmes. In this manner, ideally, an iterative process between material R&D and design could effectively progress. Unfortunately, in fusion the lack of dedicated irradiation facilities simulating sufficiently close the operating conditions of irradiated materials impedes this process.

Hence, the engineering design process has to become actively materials-related, while materials development must closely follow engineering design process needs. This results in the indispensable interaction between materials- and component design processes (see Fig. 1).

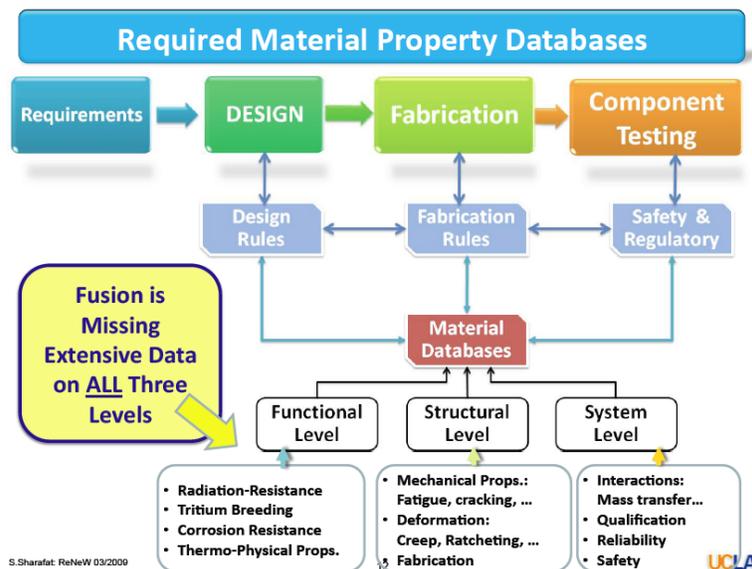


Fig. 1 Required Material Property Databases, schematic taken from presentation of S. Sharafat, B. Odette made a US ReNew Community Workshop March 2-6, 2009.

For the purpose of this assessment and similarly to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degree of extrapolation from the today's known underlying physics and engineering basis if needed should be considered.

- DEMO Model 1: a "conservative baseline design" i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.

- DEMO Model 2: an “optimistic” design, i.e, a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

Option 2 is a DEMO design that comes later in time and as such can be based on more advanced material and technology solutions.

A preliminary set of technical characteristics and parameters describing these two options is provided in a memo by D. Ward and G. Giruzzi, Proposal of Preliminary Machine Parameters for Initial Assessments, version 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters.

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

### **Review Assignments**

One of the main goals of these activities should be the preparation of a preliminary material assessment report, which gives the justifications and includes the recommended properties used for the design analysis and identify areas of uncertainties and conditions (relevant to the design) where data are instead either missing or unreliable. A tentative outline proposed for the Material Assessment Report for DEMO conceptual Design Activities is included in Annex A.

The following activities are proposed:

- Review the current material data or knowledge base for austenitic stainless steels, RAFM – steels (EUROFER), EUROFER ODS (9% Cr), ODS Ferritic steels (12-14 Cr), Tungsten and Tungsten alloys, Vanadium and Vanadium alloys, Cooper alloys, and SiC/SiC composite relevant for fusion devices beyond ITER.
- Clearly and uniquely define a material (chemical composition, fabrication process, level of development, e.g. industrial available vs. lab scale), in particular:
  - Compile for each of the materials mentioned above, all physical and mechanical data needed for design (for a full list see e.g., Appendix A. Gen of the ITER structural design code). In particular, clearly indicate if measurements techniques deviate from standards (eg ASTM);
  - Indicate and describe fabrication processes and semi-finished products available and limitations in fabrication or machining;
  - Review data from irradiations campaigns, for displacement damage and, as far as possible, He and H /dpa ratio production levels of relevance for DEMO design. In any case clearly indicate the origin of data and irradiation conditions (irradiation source, reactor, spallation etc)

- For each material considered, generate a design space in terms of operating limits (temperature, stress levels, exposure times, life time.). Try to identify areas of safe operation versus areas definitely excluded. [Notes (i) there is no unique approach, it may depend on the material and its relative state of development (ii) in-between safe design space and areas not recommended to be used there is design space where it is up to the choice of the engineer and designer].
- Identify and clearly describe the key issues and limiting factors and/or properties (eg as function of parameters like maximum stress, exposure times, neutron fluence, irradiation temperature.)
- Identify R&D needs/requirements and define milestones with time period as of 5, 10, 15 years.
- Review the benefits and define a possible IFMIF accompanying programme, i.e., coherent strategy for material qualification for DEMO complementary to IFMIF and identify potential use of fission reactors, ion beam irradiation stations, EU spallation n-sources; potential exploitation of EVEDA, and the role of modeling.

## **Available Technical Documentation**

### **A) General review articles on material databases**

- [1] F. Tavassoli, Present Limits and Improvements of Structural Materials for Fusion Reactors, *J. Nucl. Mater.* **302** (2002) 73-88.
- [2] E.E. Bloom, S.J. Zinkle, F.W. Wiffen, Materials to deliver the promise of fusion power – progress and challenges, *J. Nucl. Mater.* 329–333 (2004) 12–19.
- [3] B. van der Schaaf, E. Diegele, R. Laesser, A. Moeslang, Structural materials development and databases, *Fus. Eng. Des.* 81 (2006) 893–900.
- [4] N. Baluc, Material degradation under DEMO relevant neutron fluences, *Phys. Scr.* T138 (2009) 014004 (6pp).

### **B) EUROFER and ferritic/martensitic steels**

- [5] Bob van der Schaaf, C. Petersen, Y. De Carlan, J.W. Rensman, E. Gaganidze, X. Averty, High dose, up to 80 dpa, mechanical properties of Eurofer 97, *J. Nucl. Mater.* **386–388** (2009) 236–240.

### **C) ODS ferritic and ferritic/martensitic steels**

- [6] D.A. McClintock, D.T. Hoelzer, M.A. Sokolov, R.K. Nanstad, Mechanical properties of neutron irradiated nanostructured ferritic alloy 14YWT, *Journal of Nuclear Materials* 386–388 (2009) 307–311.
- [7] N. Baluc, J.L. Boutard, S.L. Dudarev, M. Rieth, et al., Review on the EFDA work programme on nano-structured ODS RAF steels, *Journal of Nuclear Materials* (2010), in press.

### **D) Tungsten**

- [8] M. Rieth, J. L. Boutard, S. L. Dudarev, et al., Review on the EFDA programme on tungsten materials technology and science, Journal of Nuclear Materials (2010), in press.

### **E) Copper Alloys**

- [9] P. Fenici, D.J. Boerman, G.P. Tartaglia, J.D. Elen Effect of fast-neutron irradiation on tensile properties of precipitation-hardened Cu-Cr-Zr alloy, J. Nucl. Mater. **212-215** (1994) 399-403
- [10] S.A. Fabritsiev, S.J. Zinkle, B.N. Singh, Evaluation of copper alloys for fusion reactor divertor and first wall Components J. Nucl. Mater. **233-237** (1996) 127- 137
- [11] S.J. Zinkle, N.M. Ghoniem, Fus. Eng. Des. **49-50** (2000) 709.
- [12] S. Majumdar, G. Kalinin, J. Nucl. Mater. **283-287** (2000) 1424.

### **F) Radiation Modelling and Experimental Validation.**

- [13] S.L. Dudarev, , Journal of Nuclear Materials 386–388 (2009) 1–7.
- [14] J.L. Boutard, S. Dudarev, M. Rieth, , J. Nucl. Mater. – to appear.
- [15] J.L. Boutard, A. Alamo, R. Lindau, M.Rieth, C. R. Physique 9 (2008) 287–302.
- [16] Georges Martin, Modelling materials driven far from equilibrium, Current Opinion in Solid State and Materials Science

### **Deliverables/ schedule**

This activity is expected to last for 4-6 months. The results of this assessment will be documented in comprehensive material-assessment report (see tentative outline below to be submitted with an executive summary including the key findings and recommendations.

Contributions to this report must be done at the highest level of expertise and scientific excellence.

# MATERIALS ASSESSMENT REPORT FOR THE PURPOSE TO CONDUCT DEMO CONCEPTUAL DESIGN STUDIES.

## OUTLINE

### 0. Executive summary

#### 1. Introduction

- *Main objectives and scope of this document*

*Main characteristics of fusion devices, comparison with fission environment [details in Annex]*

*Short reference to road map (ITER DEMO FPP and potential intermediate steps) and impact on materials [details in Annex]*

*Materials R&D; Description of EU portfolio & short review of EU work programmes [Details and comparison with other programmes, i.e. US, Japanese, Indian and Chinese in Annex]*

*[it is included above]- Short excuse on the key role of materials for the success of DEMO and FPP.*

#### 2. Blanket and Divertor

*Top level requirements: Safety, environment aspects, waste management and impact on materials (chemical tailoring, exclusion of materials/coolant options, T-limits, passive cooling, T-inventory ...)*

- *In vessel components. General requirements & assumptions & main functions (heat load, neutron flux (FW vs rear), replaceable, estimated fpy required, environment & compatibility*

##### 2.1 Blanket concepts (water, He- cooled and liquid metals)

*Discussion of design options (coolant, T-window, structural materials, breeder material, neutron multiplier)*

- *Design requirements. Key properties (mechanical and/or physical)*
- *List of Description of the blanket: breeding (liquid + ceramics)*

##### 2.2 Divertor concepts (water, He cooled)

*Discussion of design options (coolant, T-window, structural materials, protection/armour).*

- *Design requirements. Key properties (mechanical and/or physical)*
- *Description of the divertor functions: Heat removal, and safe and reliable operation of the machine.*

*Mention liquid divertor, but there is not effort on this topic, therefore it is not going to be discussing in this report*

### **3. Effects of the neutron irradiation on materials**

- *General introduction about the presence of radiation into the machine*
- *dpa map for different parts of the machine (Divertor and Blanket)*

#### **3.1 Blanket issues related to the presence of radiation**

- *Degradation of key properties of materials for the component function under irradiation: mechanical and physical properties.*
- *He/H production*
- *Design limitations*

#### **3.2 Divertor issues to the presence of radiation**

- *Degradation of key properties of materials for the component function under irradiation: mechanical and physical properties.*
- *He/H production*
- *Design limitations*

### **4. Present status of R&D on materials (in EU and outside of EU)**

*Guidelines for each material:*

- *Describe typical available semi-finished products (plates, rod, tube,.. sizes)*
- *Physical properties*
- *Mechanical properties*
  - o *A typical list can be copied from A.GEN of ITER SDC*
- *Fabrication and machining Joining techniques (availability processes and geometrical limits)*
- *Temperature range of operation (conservative approach and possible margins)*
- *Key issues + limiting factors + dangerous regions*
- *Data base: links with the Annexes C*
- *Possible synergies with fission*
- *Lack of information: needed experiments + justification*
- *Define milestones for R&D.*
- *Shortly describe R&D needed within the 5-10(-20) years*

#### **4.1 Austenitic stainless steels (316)**

#### **4.2 RAFM – steel development (EUROFER)**

#### **4.3 EUROFER ODS (9% Cr)**

#### 4.4 ODS steels (12-14 Cr)

#### 4.5 Tungsten and Tungsten alloys

- Different requirements for W and W alloys acting as armor or structural material

#### 4.6 Cooper alloys

#### 4.7 SiC/SiC composite

- For the blanket. Only as structural material, not for Plasma facing →  $\lambda$  degrades a lot. Thermal strains beyond permit.

#### 4.8 New concepts: foils, fibre – fibre matrix interphase and matrix, etc.

### **5. Joining techniques**

### **6. Functional materials**

### **7. Materials Irradiation Qualification – Requirements**

7.1 Available irradiation devices (neutrons and ions)

7.2 IFMIF

### **8. Modelling**

### **9. Materials availability**

### **10. Conclusions**

### **9. Recommendations**

*On R&D, on irradiation campaigns,*

*Prioritization and planning schedule (urgency vs mid term/long term)*

*Cost estimations*

### **ANNEXES A**

A1 Fusion vs. Fission

A2 DEMO vs ITER

A3 Status of R&D in EU

A4 Status of R&D outside of EU

**ANNEXES B**

- B1 Level of radiation and dpa map for the Blanket
- B2 Level of radiation and dpa map for the Divertor

**ANNEXES C**

*Engineering data for design (tables, formulae, figures) either from existing material appendices (App ) of RCC-MR, ITER-SDC or “best estimations”*

- C1 Austenitic stainless steels (316)
- C2 RAFM – steel development (EUROFER)
- C3 EUROFER ODS (9% Cr)
- C4 ODS steels (12-14 Cr)
- C5 Tungsten and Tungsten alloys
- C6 W alloys acting as armor or structural material
- C7 Vanadium and Vanadium alloys
- C8 Cupper alloys
- C9 SiC/SiC composite

**IFMIF accompanying programme**

- Periodic annealing of radiation damage – experimental verification (including Helium)
- Ion irradiation
- Irradiation 500-600C for EUROFER is missing
- Void swelling (in the presence of He) in the 400C-500C – 550C 600C temperature range
- Low T irradiation required for water – cooling (100-150 C)
- Corrosion resistance, under irradiation at high T
- High temperature irradiation programme for W, refractory alloys.
- Miniaturized specimens, an number of specimens for one series of experiment

[6]

## **EVALUATION OF THE TECHNOLOGY/ ENGINEERING ISSUES OF PULSED VS. STEADY-STATE TOKAMAKS FOR POSSIBLE APPLICATIONS IN FUTURE FUSION REACTORS**

### **TERMS OF REFERENCE**

**27.5.2011**

#### **Preamble**

These terms of reference describe the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to evaluate the technology/ engineering issues of pulsed vs. steady-state tokamaks for possible applications in future fusion reactors.

These ToR were prepared as a result of a preparatory meeting involving experts of Associations and Industry that was held at EFDA CSU Garching on May 10-11, 2011. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

#### **Background**

In tokamaks, steady state operation means non-inductive operation where the plasma current is driven by a combination of intrinsic ('bootstrap') current and current externally driven by H&CD systems. The former implies operation at high normalised plasma pressure  $\beta_N$ , challenging the stability limits, the latter implies a large burden on the economic efficiency since the external H&CD system has to be powered by the electrical energy generated by the plant itself. A credible tokamak scenario with very high bootstrap fraction exists on paper, but has not yet been convincingly proven experimentally. We note that this not only requires that the full current is driven non-inductively, but also that the radial profiles of current density and pressure are self-consistently aligned for plasma equilibrium and stability. Hence, this is an area where physics R&D will be needed.

Present-day extrapolations of plasma current drive efficiency in tokamak reactor scenarios, combined with the anticipated poor efficiency of converting wall-plug power into power coupled into the plasma, lead to very large recycled power fractions in steady-state tokamak reactor designs. This problem is exacerbated by the thermodynamic conversion efficiency of the fusion output power, and by the requirement for the large grid demand for the current drive system (if this is significantly larger than the heating power required to achieve ignition or high-Q operation) during start-up of the machine.

The substantial debit on the whole-life cost balance of the machine that steady-state current drive thus engenders could be saved if the reactor was allowed to operate in pulsed mode, but this in turn raises many questions affecting the design of the machine and raising the cost of substantial elements of the structure.

While countries with centrally controlled national grid feeds and loads can readily accommodate transients (even sudden transients such as loss or reinstatement of GW-scale undersea links) by dint of a spectrum of facilities and operational adjustments, it remains the case that the electricity supply industry would greatly prefer a steady state (or load-following) generation capability over one that was intrinsically pulsed. This implies that a pulsed fusion reactor would require some form of energy storage to smooth out its net feed to the grid. This need not be a firm requirement for a first-generation DEMO reactor however, especially as the availability of the first DEMO can be expected to be modest (say ~20% rising to ~60% as operational experience is accumulated). Even so, it may be necessary to have a modest energy store to permit reactor start-up without impacting the grid.

However even if a full output-smoothing energy store were to be included, or the national grid companies were prepared to accept an ensemble of pulsed power generation systems, the individual pulsed reactors have to be designed to survive the severe thermomechanical stress cycling that the pulsing would entail, together with a much larger number of electromechanical stress cycles than is intended for steady-state design variants. The electromagnetic stresses affect not only the support structures of the coils but also the strands of the superconducting cable within the conductor, which degrade in performance when under strain and also as a result of being subjected to large numbers of strain cycles, both electromechanical and thermomechanical in origin. Naturally significant relevant material exists in the ITER design, since this machine is intended to have a cyclic life of some tens of thousands of plasma pulses and several hundred toroidal field excursions.

Accordingly this technical review assignment has to address *inter alia* the present state of thinking on likely plasma burn and dwell durations (and hence number of cycles required over a given operational life), thermomechanical creep fatigue in plasma facing components and coolant circuits, the optimisation of reactor load assembly design for the intended number of cycles; high-power, short-duration energy storage systems (on the scale of GW sustained for many minutes), the balance of cost of energy storage against the cost of solenoid recharge power supply requirements, the pros and cons of an AC plasma current design, and superconductor performance degradation with strain and fatigue.

For the purpose of this work and similar to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a preliminary set of parameters describing a typical DEMO pulsed power plant is provided in a memo by D. Ward and G. Giruzzi, Proposal of Preliminary Machine Parameters for Initial Assessments, version. 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters and the resulting changes in the reactor performance, whole-life cost etc. Similarly, the basis for engineering design assessments should ideally be standardised, such as fatigue life assessments (e.g. number of standard deviations below S-N curve data, or stated initial flaw size for a fracture mechanics approach).

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

## Available Technical Documentation

Some technical documentation available on these subjects is shown below but there is no authoritative set of documents that provides unequivocal answers to the questions elaborated in the next section. A key part of the review activity will be the identification and engagement of knowledgeable design and research specialists who can provide information or point to literature that addresses the points of interest.

T N Todd, R Clarke, H Kalsi, M Kovari, Andrew Martin, A Muir, Z Vizvary, The key impacts of pulsed operation on the engineering of DEMO, Culham (internal) Milestone Report C5.M4, February 2010 [*This report includes over 80 pertinent references, including the two marked \* below.*]

I. Cook, D. Maisonnier et al., European Fusion Power Plant Studies, TOFE conference,

D. Maisonnier et al., DEMO and fusion power plant conceptual studies in Europe

M. Abdou, R. Raffray, M. Tillack, A. Hadid, Impact of pulsed and steady-state plasma operation on nuclear testing in TIBER/ ITER, ITER Nuclear Performance Analysis Group Meeting 27-29 May 1987.

C.G. Bathke and the ARIES Team, A comparison of Steady-State ARIES and Pulsed PULSAR Tokamak Power Plant, Fusion Technology 26 (1994) 1163-1168.

J. Crowell, J. Blanchard and the PULSAR Team, Fatigue life of the plasma facing components in PULSAR, Fus. Eng. Des. 27 (1995) 515-521.

Pulsed Fusion Reactor Study, Final Report, Electrowatt – Consulting Engineers and Scientists, Aug. 1992.\*

D.A. Ehst, Y. Cha, A.M.Hassanein, S. Majumdar, B. Misra and H.C. Stevens, Nuclear Engineering and Design. Fusion, A comparison of pulsed and steady-state tokamak reactor burn cycles. Part I: Thermal effects and lifetime limitations , Volume 2, Issue 3, 1985, 305-318.

D.A. Ehst, J.N.Brooks, K.Evans Jr. and S. Kim, A comparison of pulsed and steady-state tokamak reactor burn cycles. Part II: Magnet fatigue, power supplies, and cost analysis, Nuclear Engineering and Design. Fusion Volume 2, Issue 3, 1985, 319-336\*

Michael Kovari, Stress and fatigue in the magnets in DEMO in pulsed and steady-state operation using geometric scaling factors, SOFT 2010.

Zsolt Vizvary, Panos Karditsas, Thermal Fatigue of DEMO First Wall Due to Pulsed Operation, SOFT 2010

## Detailed Review Assignment Questions

Tokamak reactor systems codes such as PROCESS can be used to address some of the basic questions regarding such things as likely burn duration, reactive power needed to recharge the OH solenoid and their variations with engineering and plasma parameters. Operational options to be checked include the optimised proportion of plasma current

that can be driven non-inductively by the plasma heating system necessary to achieve and control the high-Q regime, i.e. how best to divide that between the fractions carried by boot-strap current (needing high plasma density) and direct current drive (needing low plasma density), and the overall cost-benefit ratio of recycling electrical power for this purpose. Conventional mechanical design approaches can be used to determine the increase in reactor mass (and hence cost) necessary to allow the structure to accommodate the cyclic loads without suffering premature fatigue failure, where the structure is not significantly exposed to neutron irradiation (e.g. in and around the magnet windings). However if possible, it would be desirable to develop a plausible algorithm to embed into a reactor systems code in order to address the increased cost of accommodating the larger number of stress cycles of the pulsed variant as a function of the lifetime number of pulses, to permit an optimum to be found. AC operation of a poloidal divertor tokamak would obviate the problem of recharging the solenoid between pulses but introduces the problem of tile-tile alignment tolerances, presently dealt with by “imbricating” (ski-ramping) the surfaces of the tiles so that each shadows its neighbour – but only for one direction of the plasma current. The shadowing reduces the “wetted area” and hence the power handling capability, which would be exacerbated with bidirectional imbrication. If the machine featured two poloidal divertors, one for each plasma current direction, there is a cost penalty and also only one of them would be in the direction of the grad-B ion drift which favours H-mode access. Thus the possibility of AC operation requires careful cost-benefit analysis covering many more design aspects than just the solenoid power supply.

The comprehensive testing of superconductors under significant strain and with significant strain modulation appears to be a developing field, especially for Nb<sub>3</sub>Sn as is likely to be favoured for the solenoid and toroidal field coils of first-generation fusion reactors. University research (Durham in the UK) and tests undertaken for ITER represent starting points for the review in this vitally important area. Since many of the problems of Nb<sub>3</sub>Sn lie with the use of cable-in-conduit-conductor (and its precise fabrication details), significant benefit could accrue from adopting a different type of conductor which does not allow the superconducting filaments to suffer any significant strain when subjected to varying magnetic fields. Part of the review activity should therefore address the progress in such conductor development, hoping to find a well-proven design concept from another field, or else to specify a way forward for new conductor fabrication and trials.

Industry is exploring many different ways of storing energy and turning it into electricity for the grid, some traditional and some novel, and with much variation in total energy stored and electricity generation capability (resulting in different problems of scaling up to say 400MW<sub>e</sub>hr regenerated at 1.5GW<sub>e</sub> for output smoothing or far less, say 75MW<sub>e</sub>hr regenerated at 300MW<sub>e</sub>, for reactor start-up with negligible grid impact). One important choice if any type of energy store is required will be whether to store heat (with associated storage losses and thermodynamic efficiency issues when recovering the energy) or highly ordered energy such as electrical or mechanical (where the loss during storage can be very small and the efficiency of reconversion to electricity can be quite high).

The nuclear fission and aerospace industries continually develop new alloys and characterise them for creep and fatigue behaviour at elevated temperatures, often of interest for fusion applications, but they do not expose the test specimens to the fast neutrons typical of a fusion reactor first wall and blanket. Thus while some test data has been obtained for particular materials of keen interest to fusion, the exercise of interest for DEMO design work will be to collate such data as is available and to check the literature for how to extrapolate it to account for neutron irradiation effects. Expert

opinion seems to be that currently the state of the art in materials modelling does not allow a theoretical approach to be used for any such extrapolation, although data trends from closely related alloys could be informative. A key part of the work of the Pulsed DEMO group should be to liaise with Working Group on the Assessment of a Material Engineering Database for Conceptual Design Studies in identifying the most important gaps in understanding of candidate first wall materials and suggesting test programmes to resolve them.

### Table of specific tasks

P1	Working Group Coordination, ensuring no overlap with the Working Groups considering materials and plasma heating and current drive.	0.2
P2	Review all readily available fusion reactor literature since 1990 and summarise the problems identified in that literature for the steady-state DEMO concepts. This should include consideration of extension of present-day heating and current drive systems and plasma-facing components to steady-state applications.	0.15
P3	Assess the variation of capital and whole-life costs of a pulsed tokamak version of DEMO with respect to the burn duration, and hence the ability to survive the number of cycles applied to the main load assembly in its lifetime (say 30 years) and to the divertor modules (lifetime say 5 years), recognising the increased cost of the load assembly if it is made to accommodate a larger solenoid flux swing in order to extend the burn duration.	0.2
P4	Assess the power and energy requirements needed for plasma initiation, ramp-up to burn and subsequent solenoid recharge in a pulsed tokamak DEMO with unidirectional plasma current, and how these requirements might be met (direct transient grid demand, thermal or electrical or mechanical energy store, or local generator such as gas turbine). Include estimates of the capital and operational costs of each option considered.	0.1
P5	Investigate COTS and present industrial development activities in large-scale energy storage systems and show how an energy store with a power capability and capacity sufficient to allow start-up and burn initiation (say ~300MWe and ~75 MWeh) could be reliably achieved in DEMO without demanding any power from the grid. Pumped water "mechanical" systems provide examples of COTS solutions that easily meet the requirements, while molten salt thermal energy stores represent up-and-coming systems already built with adequate capacity but so far with very much smaller power capability. For this initial assessment, it should be assumed that "a Pulsed DEMO" should NOT be designed to maintain a constant output	0.1

to the grid, partly because it should not be designed for a high availability, so inter-shot times are likely to be very long and the energy storage therefore impracticable.

- P6 Assess the relative merits of basing a pulsed DEMO concept on an AC tokamak. The solenoid current would not then need to be reversed between plasma discharges, greatly reducing the solenoid power supply requirement (which otherwise has to reverse the solenoid current as fast as possible) but problems arise in the divertor and the H-Mode access and ELM behaviour, if either of these is considered necessary in a reactor. The divertor tiles would probably be “imbricated” (i.e. field-line-angle specific) to avoid over-heating the edges, but for bi-directional plasma current would therefore need to be provided with this feature symmetrically, greatly reducing the “wetted fraction” and hence power handling capability. If instead two divertors were provided at opposite ends of the machine, with opposite imbrication and used alternately, then (putting aside the cost of the second divertor) the grad-B drift which affects the tokamak edge physics would be unfavourable for one of them, since it is essentially impossible to keep reversing the toroidal field as well. 0.1
- P7 Estimate the plasma heating power required to ramp up to the burn phase (ignition with independently controlled fusion power, or a high-Q scenario with control and sustainment by continuously varied power injection) and optimise the plasma to make use of this plasma heating system for current drive (and hence pulse extension and reduction of the number of cycles required in the reactor life). Include a density variation sufficient to explore efficient current drive (low density) through to efficient exploitation of bootstrap current (high density), ensuring consistency with the ignited or high-Q regime assumed but if necessary allowing the fusion output power to vary. 0.1
- P8 Develop an ansatz to indicate the variation of the cost of the reactor load assembly (i.e. the support structures) with the number of tokamak pulses in the assumed calendar lifetime (of say 30 years). This requires the construction of a model structure capturing the key elements of a DEMO design in a fully parameterised way (e.g poloidal location of inter-TF-coil struts, their thickness radially and poloidally, radii where they blend into the TF coil supports, and so on). Subsequently a series of FE analyses is required so that a scaling law of FEA results can be produced which will allow a reactor systems code to optimise the parameters so as to achieve a given number of cycles (or equivalently a given burn duration) with minimal additional cost of the load assembly. Materials data for cyclic fatigue or fracture mechanics predictions are 0.35

required for the candidate structural alloys, to provide a relationship between the stresses deduced from the scaling law and the permissible number of stress cycles or vice versa.

- P9            Develop a sub-routine to include such a parameterised ansatz    0.2  
in a chosen systems code such as PROCESS, and produce  
graphs of overall whole-life-cost vs number of cycles of  
assumed life for a selection of candidate structural materials.
- P10           Review concepts for Nb<sub>3</sub>Sn conductor construction that do not    0.2  
suffer from any significant strand motion and fatigue due to  
varying magnetic fields and propose a suitable conductor  
development and trials programme.
- P11           Assess the cost trade-offs of changing the machine design to    0.3  
reduce significantly (compared to ITER and present outline  
designs for DEMO in the literature) the total heat load (thermal  
conduction and radiation, nuclear, eddy-current and motion  
friction) on the superconducting coils, with respect to the costs  
and operational problems of tolerating the conductor heating  
and hence reduced temperature margin for a given  
superconducting current density and magnetic field strength.

#### **Deliverables/ schedule**

This activity is expected to last for 4-6 months. Clearly in such a timescale it cannot be expected to make even interim conclusions on more than a few of these questions, but the status of all the topics can be determined and the way ahead can be outlined. The results of this assessment will be documented in a comprehensive report to be submitted with an executive summary including the key findings and recommendations for further work.

[7]

## **EVALUATION OF CANDIDATE REMOTE MAINTENANCE SCHEMES FOR IN-VESSEL COMPONENTS BEING PROPOSED FOR USE IN FUTURE FUSION POWER PLANTS**

### **TERMS OF REFERENCE**

**27.05.2011**

#### **General**

These terms of reference describes the review assignment work to be conducted as part of the EFDA Power Plant Physics & Technology Work Programme 2011 to evaluate the remote maintenance<sup>1</sup> schemes for future Fusion Power Plants (FPPs).

These ToR were prepared as a result of a preparatory meeting involving experts of Associations and Industry that was held at EFDA CSU Garching on May 10-11, 2011. They are intended to provide a clear definition of (i) specific questions to be addressed or activities to be carried out in the course of the study via EFDA tasks to be launched in 2011; (ii) specific areas where Industry can provide support to the review assignments; and (iii) background technical information (e.g. scientific papers and technical reports) available on each specific area, and which would facilitate the assessment work.

Although the main emphasis is on the maintenance of in-vessel components, work in the future will encompass ex-vessel activities linked to the maintenance of in-vessel components, in particular their transport between the vessel and the hot cell, and ex-vessel maintenance activities proper. The proposed review activities on RAMI and on standardisation should therefore not be limited to in-vessel maintenance operations.

For the purpose of this assessment and similarly to the other evaluation studies, which are being launched in the context of the Power Plant Physics and Technology (PPPT) Work Programme 2011, a limited number of possible bounding DEMO design concepts with various degree of extrapolation from the today's known underlying physics and engineering basis if needed should be considered.

- DEMO Model 1: a “conservative baseline design” i.e. a DEMO concept deliverable in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.
- DEMO Model 2: an “optimistic” design, i.e, a DEMO concept based around more advanced assumptions which are at the upper limit of what may be achieved during the ITER phase of fusion development, i.e., an advanced higher power density high CD steady state plasma scenario. It is clear that this can only be delivered on a longer term.

A preliminary set of technical characteristics and parameters describing these two options is provided in a memo by D. Ward and G. Giruzzi, Proposal of Preliminary Machine Parameters

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<sup>1</sup> Maintenance shall be considered as meaning "maintenance and inspection"

for Initial Assessments, version 13.5.2011). Please note that this is only the start of the process to produce reference designs for DEMO and these should not be considered as reference EU DEMO designs but just sets of parameters to allow assessments to begin. Deviations could be made in the studies where appropriate but with a clear reference to the changes made in the assumed parameters.

In addition, the parameters/ technical characteristics of these options are expected to be consolidated as part of the preliminary design oriented activities to be conducted this year as part of the activities on the system code, being conducted under the PPPT WP2011.

The review in 2011 shall be co-ordinated jointly by a representative from the Associations and a representative from Industry.

### **Key requirements**

The development of remote maintenance schemes for future FPPs shall be driven by the following key requirements: (1) feasibility and reliability of the maintenance schemes, (2) high machine availability, resulting in a maximum duration for the execution of the various maintenance operations and/or the need to carry out several maintenance operations in parallel. This work is particularly crucial because the ITER maintenance scheme for in-vessel components is not reactor-relevant, so that novel maintenance concepts must be developed and validated for use in DEMO.

Although not directly relevant, several important lessons will be learned from RH activities in ITER and in JET. It will therefore be essential to establish and to maintain close links between the persons involved in the DEMO/FPP remote handling activities and their colleagues in JET and in ITER.

### **Technical Documentation**

- [1] D. Maisonnier, et al., Power plant conceptual studies in Europe, Power plant conceptual studies in Europe, Nucl. Fusion 47 (2007) 1524–1532  
([http://www.iop.org/EJ/article/0029-5515/47/11/014/nf7\\_11\\_014.pdf](http://www.iop.org/EJ/article/0029-5515/47/11/014/nf7_11_014.pdf))
- [2] European Power Plant Conceptual Study, full PPCS report  
([www.efda.org/eu\\_fusion\\_programme/scientific\\_and\\_technical\\_publications.htm](http://www.efda.org/eu_fusion_programme/scientific_and_technical_publications.htm))
- [3] D. Maisonnier, European DEMO Design and Maintenance Strategy, Fusion Engineering and Design 83 (2008)
- [4] Special Section on Safety Aspects of Fusion Power Plants, Nuclear Fusion 47, volume 7, <http://www.iop.org/EJ/toc/0029-5515/47/7>
- [5] S. Malang, et al., ARIES-RS maintenance approach for high availability, Fusion Eng. Des. 41 (1998). 377-383.
- [6] S. Ueda, et al., Maintenance and materials aspects of DREAM, Fusion Eng. Des. 48 (2000) 521–526.
- [7] The European Fusion Research Programme: Positioning, Strategic outlook and need for infrastructure towards DEMO, PART II: facilities, EFDA, 6 May 2008.
- [8] R&D Needs and Required Facilities for the Development of Fusion as an Energy Source, Report of the Fusion Facilities Review Panel October 2008.
- [9] J. Pamela, A. Bécoulet, D. Borba, J.-L. Boutard, L. Horton, D. Maisonnier, Efficiency and availability driven R&D issues for DEMO, Fus. Eng. Des. 84 (2009) 194-204.
- [10] Appendix 9, EU Power Plant Conceptual Study – Maintenance, EFDA(05)-27/4.10 revision 1 (revision 0: STAC 10/4.1).

- [11] Julie Bonnemason, Jean-Pierre Friconneau, David Maisonnier, Yann Perrot, Contribution to DEMO reactor RH maintenance assessment, Fus. Eng. Des. 84 (2009) 480–484
- [12] P. Batistoni, S. Clement Lorenzo, K. Kurzydowski, D. Maisonnier, G. Marbach, M. Noe, J. Paméla, D. Stork, J. Sanchez, M.Q. Tran (Chair) and H. Zohm, Report of the Ad-hoc Group on DEMO Activities, March 2010 - Revision June 2010.

### Detailed Review Assignments

- a) Task Coordination
- b) Review the ITER/PPCS divertor maintenance scheme to confirm its reactor relevance in 2011. Define the activities to be carried out in this area in 2012-2013.
- c) Review the potential of the “banana” blanket handling concept for DEMO/FPP. Define the activities to be carried out in this area in 2012-2013.
- d) Consider possible alternative plant architectures which may take into account completely different maintenance schemes (e.g., upper divertor and extraction of blanket segments from the bottom of the machine relying on transfer gallery below ground level, easier draining of components, no huge loads suspended during in-cask etc.), with a view to achieve more effective maintenance schemes. Preliminary work is to be carried out in 2011, to be followed by a more detailed assessment of the proposed schemes in 2012-2013.
- e) Define the design and R&D activities on the connections of in-vessel components (mechanical, hydraulic etc.) to be carried out in 2012 and beyond.
- f) Identify the ex-vessel and hot-cell maintenance operations and the logistics aspects to be studied in more detail in 2012-2013.
- g) Preliminary definition of the DEMO port plugs. Significant differences are expected between the pulsed and the steady-state devices, so that these 2 options ought to be considered separately. This action is to be carried out in collaboration with other DEMO designers. Identify further work, to be carried out in 2012-2013.
- h) Define a tentative radiation map in DEMO (if possible in 2011 by scaling from similar radiation maps available for ITER) during a plasma pulse and at different points in time after termination of a plasma shot (1hr, 1d, 1w, 1m, 6m). Identify further work to be carried out in 2012-2013 – if appropriate – to refine the radiation map.
- i) Establish RAMI guidelines for all major sub-systems. This activity will be carried out in 2011 and 2012, and a first interaction with experts in the various fields should be foreseen in 2013.
- j) Define a methodology for the definition of standards. This activity will be carried out in 2011, 2012 and 2013. The work to be carried out in 2012-2013 shall be clarified in 2011.

### Resources (indicative breakdown, in ppy)

Task Coordination: 0.4 (total 0.4 ppy)

b) and c): 0.4 each (total 0.8ppy)

g) 0.2 (total 0.2ppy)

All other items: 0.1ppm (total 0.6ppy)

