Mid-Term Work Package Progress Status Report

Work Package	***Materials***
Work Scope	*The **primary objectives** of the Materials Project are to* • *Improve the maturity of the portfolio of „baseline materials“, including “Structural materials” (EUROFER), “Plasma facing armour materials” (Tungsten) and “High heat flux – heat sink materials” (Copper alloys)* • *Validate the baseline materials towards „code qualified materials“ together with parallel consistent specific design rules* • *Develop in parallel „Advanced material options“ for enhanced operation and as a strategy of general risk mitigation in component design areas* *The scope includes:* *(i) **„baseline materials“*** • *The establishment of a series of materials property handbooks (consolidated data)* • *A first set of assessed material data as required for appendices in design codes* *(ii) **“new materials”*** • *Development of new materials to provide options for advanced DEMO component designs* • *Demonstration of the production of such materials in processes scalable to industrial standards* • *Characterization of the properties of such materials* *(iii) **“increasing fundamental knowledge of materials in service”*** • *Model, predict, validate and determine material properties under DEMO-relevant neutron irradiation*
Report compiled by	*M. Rieth, E. Diegele*
Other Participants	*SCK.CEN, CCFE, CEA, CIEMAT, DTU, ENEA-CNR, ENEA-Frascati, FOM-NRG, FZJ, HAS, NCSRD, IPP, IST, KIT, IAP (MEDC), JSI (MESCS), ÖAW, RBI, TEKES, TEKES-TARTU, UL, VR*
Project Delivery Date	*31/12/2018*
Reporting period	*Jan 2014 – Dec 2015*

1. PROGRESS SUMMARY

- Engineering Data and Design Integration (EDDI)

EDDI has sought to facilitate structured discussions with all EUROfusion projects and work packages that need to exchange materials information. An **Interface Management Plan** connecting all projects and work packages that need to interact with WPMAT has been produced, with supporting, controlled documents for the exchange of materials requirements, testing capabilities and test specifications. A **Materials Technology Readiness Level (MTRL) system** was completed and applied to produce reports for 30 materials. EDDI has focussed on the provision of basic infrastructure for the storage of immediately available and newly produced data. After an initial delay due to legal issues (property rights of materials data) impressive efforts to collate the accessible data for EUROFER97 have been undertaken. Data has been successfully filtered against established quality criteria and various allowables have been calculated. This has then formed the basis of a first draft **DEMO Material Property Handbook**. The structure of the **DEMO-specific Design Criteria (DDC)** has been produced and populated in part with selected draft content and is now subject to on-going peer review. One of the critical successes of this work stream has been the initial incorporation of plasticity rules into the DDC, strategically advancing on existing nuclear codes and modernising the DEMO approach. A **Creep-Fatigue tool** has been extensively developed for application within ANSYS and will be rolled out to design teams. Further work has been undertaken on **Design Rules Development** focusing on ratchetting, fatigue, brittle fracture and creep-fatigue.

- Advanced Steels (AS)

The sub-programme focuses on the following lines of development: (a) RAFM (Reduced activation ferritic-martensitic) steels, EUROFER “Low Temperature (LT)”, with improved chemical composition for an increased operation temperature range at the lower end for use with a water cooled blanket, (b) RAFM steels, EUROFER “High Temperature (HT)” with improved composition and/or thermo-mechanical treatment to enhance properties at the high end of the T-window, (c) complementary development of ferritic (14 Cr) ODS (oxide dispersion strengthened steels) for HT applications and improved neutron resistance.
The activities performed under the AS subproject have made very good progress. **More than 30 new alloys** specified in 2014 as either EUROFER-LT or EUROFER-HT options have all been cast. More in-depth characterization is still on-going.
The results so far demonstrate that the development of 9Cr steels for HT applications is a realistic goal: for instance a **significant improvement of EUROFER-HT mechanical properties** can be obtained with modified heat treatments (compared to standard heat treatment of EUROFER-97), with optimized chemical compositions and by thermomechanical treatments. To develop 9Cr steels, which combine significantly better high temperature strength and creep behaviour than EUROFER-97, and with comparable or even better impact-toughness properties is very well possible and achievable in time.
The development of 9Cr steels for “LT” applications is a really challenging objective. Some improvement of impact properties in the “as-received” condition has already been obtained and new treatments on optimized compositions may yield more significant gains. Irradiation with ions and neutrons will be used to screen the new alloys and assess their irradiation performance at low temperatures. In any case, the down-selection of successful metallurgical strategies will take place during 2016 as planned.
ODS development: Both the fabrication of a large ferritic ODS batch and of a FW mock-up are well on track (**mechanical alloying of a 140 kg batch**). The development of an alternative cost-efficient process by CEIT is progressing. However, the mechanical strength of ODS produced with the new route needs to be improved and the possibility to up-scale to industrial fabrication has yet to be demonstrated.

- High Heat Flux Materials (HHFM)

The development within the HHFM project has made **significant progress in various areas**, including:

- plasma facing materials: particle and fiber reinforced W materials fabricated by technologies without final deformation step
- heat sink materials: particle and fiber reinforced Cu-based materials
- W-laminates and W-fiber reinforced W, which are investigated as plasma facing as well as heat sink materials
- joints (W/Cu or W/CuCrZr, W/steel) and
- interfaces, e.g. thermal barrier layers and W/Cu-Functional Graded Materials (FGMs).

In particular the amount of available data from detailed **mechanical, thermo-physical and high heat flux characterization** is steadily increasing and transferred to the newly established **material database by EDDI**. The interaction between the different RUs with respect to the individual material development has been strengthened to exploit available synergies and to benefit from existing know-how distributed all over Europe. In many cases the former newly developed **fabrication technologies** became significantly more mature which is expressed by the increasing optimization degree of the manufactured materials. However, due to this increasing maturity and the resulting possibility for an evaluation and qualification of different materials and technologies it was also possible to **down-select fabrication technologies and material combinations**, which have been considered not suitable for further use in the development of high heat flux materials and components.

- <u>Functional Materials (FM)</u>

FM addresses dielectric and optical reference materials for DEMO. The **radiation stability of metallic mirrors** has been tested at higher doses in ion irradiation including He effects. Promising transparent ceramics were assessed and down-selected for future irradiation tests. For the first time, **several sintering methods** have been systematically tested for **alumina dielectric properties.** By applying self-doping processes first reproducible results in low loss tangent values have been obtained, which confirm the applied development strategy. Surface dielectric properties of **commercial diamond windows** have been characterized using different surface treatments, resulting in three options to be further considered and tested under high MW power. **Modelling of alumina** has been started to strengthen the understanding of the underlying damage processes.

- <u>Integrated Radiation Effect Modelling and Experimental Validation (IREMEV)</u>

The IREMEV sub-project **has now accumulated the knowledge and expertise** necessary for making the next step in the treatment of radiation induced microstructure as a real-space entity and then using this information **as input for dislocation-based simulations of plasticity**. The **development of realistic and experimentally verified models for the evolution of irradiation driven microstructure and for the response of such microstructures to loading** is a clearly defined objective for IREMEV for 2016 and beyond. This goal is extremely challenging and demanding, and will require extensive intellectual, mathematical and computational effort. Given the scarcity and fragmented nature of experimental information, this is a practically viable way forward in the assessment of performance of materials under the expected fusion irradiation conditions.

- <u>Neutron Irradiation and Examination (IRRAD)</u>

After approval of the GA, within this subproject **six irradiation campaigns will be launched in 2016**. The campaigns will contribute to the baseline materials database (EUROFER, CuCrZr, W alloys), to the screening of advanced steels, and to the validation of models (W, W-Re alloys). The irradiations will be performed in HFIR (ORNL, USA), BR-2 (Mol, Belgium), and LVR-15 (Rez, Czech Rep.) and post-irradiation examination will be performed in various RUs (e.g. CEA, NCSRD, KIT, FZJ, SCK.CEN, IPP.CR).

2. MATURITY ASSESSMENT

- Requirements: Target values (material properties, benchmarks, process limits, cost) for advanced materials development and for all EDDI subproject activities have been defined in collaboration with BB and DIV.
- Decision tree: first down-selection of steels in 2016; main decisions are only possible after basic irradiation performance data are available.
- Technology readiness assessment: MTRL system applied to baseline and all newly developed materials
- Industrial engagement and future plans: in AS, FM, HHFM sufficient; higher involvement for EDDI in preparation.
- Interface definition status: Interface Management Plan finalised and in operation.

3. RISKS, ISSUES, CHALLENGES	4. RISK MITIGATION, DEVIATION OF THE PROGRAM
A detailed risk register is specified (derived from MAG report) in Annex14_Risk_Register_2LWSTD_v1_0. It addresses mainly material properties. Based on the strategy and assumption that the pre-conceptual design phase considers only baseline materials, that is, the components will be designed using baseline materials (EUROFER, CuCrZr, OF-Cu, tungsten) only. In this context, RISK was defined as „risk of failure in component design due to insufficient material	

properties". In other words, this is the risk that baseline materials do not suffice to the design requirements in terms of analysis and criteria for operation. Therefore, the terms „advanced materials" and „risk mitigation materials" were introduced and the work programme was structured to mitigate these risks from other projects. Additionally, irradiation campaigns have to be performed tot o close gaps in the database of baseline materials. The risk that baseline materials might not meet design criteria after irradiation or that the development of advanced materials with improved properties does not succeed, is not an issue of the MAT risk register by itself.	
PROBLEM: The origin of these risks is NOT within WPMAT. About 80% of the MAT work programme is actually „risk mitigation for engineering activities in BB, DIV and other projects that are following the over-all loading conditions".	
The real project-oriented risks in WPMAT can be summarized in one category: force majeure. Examples are delays in irradiation campaigns due to reactor operating issues, delays in material production due to failure of facilities or problems with industrial partners, staff shortage, etc.	So far, MAT has experienced three of these cases: (1) Breakdown of a gas-reaction chamber for alternative ODS steel production (industrial facility). The delay of about 1 year is partly compensated by increasing the lab-scale powder production. (2) An industrial partner for steel production (Saarschmiede) fails to produce 4 experimental heats. The possible delay of 2-3 year was fixed to 2 years by ordering heats from OCAS. (3) Problems at CCFE, NRG and HAS led to a reduction of ppy in EDDI during 2015. Therefore, the work programme has been tightened and restricted to main topics.
	In all cases, there was no programmatic deviation from the program. Only two milestones have to be postponed (Materials Handbook V1.0, industrial scale production of ODS powders). Note: In the long term, the risk related to materials development is directly connected to the availability of resources (and facilities) for comprising irradiation campaigns in due time.

5. CO-ORDINATION/ SYNERGY WITH ITER/F4E AND INDUSTRY ENGAGEMENT

Co-ordination with ITER/F4E: With F4E there is direct co-ordination and cooperation in the areas of design rules, codes & standards, baseline material properties/database, high heat flux testing standards, component fabrication processes.

There are as well synergies within the Broader Approach, where EUROfusion, F4E (TBM project) and Japan ("former" JAEA) co-operate in the above-mentioned areas and organize regularly and frequently meetings for exchange of information.

There is no dependency on the ITER program. But there is synergy with ITER technology regarding the high heat flux testing technology and standards, which are implemented in MAT as benchmark tests for armour materials and mock-ups. In addition, the ITER specifications for CuCrZr (including processing) are used as a baseline in the development of advanced copper alloys and composites.

Industry is very successfully (and with mutual benefit) involved in AS (3 steel manufacturers), in HHFM (PIM, copper and composite manufacturer, commercial sintering) and in FM (commercial producer of alumina). For 2016 and beyond, a significant industrial involvement in EDDI is planned and currently under negotiation.

6. IMPLEMENTATION SUPPORTING DOCUMENTS

- Work Break-down Structure (Annex A)
- Project Management Plan: https://idm.euro-fusion.org/?uid=2M9EBD
- Integrated Work Package Schedule and Key Milestones (Annex B)
- Activity Task Specifications: https://idm.euro-fusion.org/?uid=2LFGNA
- Work package deliverables status (Annex C) and monitoring:

  PPPT all deliverables 2014; PPPT all deliverables 2015
- Grant deliverables and work package decision logic (Annex D): Grant deliverables status
- Project Board meeting minutes: https://idm.euro-fusion.org/?uid=2GE579
- Risk register: MAG report in Annex14_Risk_Register_2LWSTD_v1_0

7. DISSEMINATION

- FPCC meeting, IEA, Paris, 28.01.2014, “Advanced Steels, Structural Materials, and High Heat Flux Components - A brief overview on the European fusion materials programme“
- SOFT, San Sebastian, Oct. 2014: Plenary talk “Integrated European Materials Programme for DEMO Applications: Recent achievements and challenges” and several other talks & posters
- 1st IAEA Technical Meeting on Divertor Concepts, IAEA HQ, Vienna, 29.09.-2.10.2015: „The European R&D Programme on Divertor Armor materials and Technology – Status and Strategy” and other talks & posters
- PFMC, 18-22 May 2015, Aix-en-Provence, France: Two presentations on HHFM topics
- 17th International Conference on Fusion Reactor Materials, October 11th - 16th, 2015, Eurogress Aachen, Germany: Plenary, invited and many regular talks and posters on all MAT topics.
- MatISSE/JPNM workshop on cross-cutting issues in structural materials R&D for future energy systems, 1-2 Nov. 2015, Petten, The Netherlands: „The EUROfusion program on 9CrWVTa steels “ and „Possible Cross-cutting Applications for EUROfusion High Heat Flux Materials“
- WPPFC Meeting, 25 Nov. 2015: „WPMAT-HHFM Research topics and actual status“
- 23rd European Fusion Programme Workshop in Slovenia from 30 Nov – 2 Dec 2015: Four out of five sessions were related to the MAT project.
- 35 journal papers on MAT topics in 2015 (see EUROfusion pinboard)

8. NEXT STEPS / INCLUDING IMPACT OF ROADMAP UPDATE

The most important next steps are:

- Implementation and start of six irradiation campaigns in different areas: (i) component design, (ii) (advanced) materials development, and (iii) basic material behaviour and validation in order (a) to fill database gaps as well as (b) to generate data for optimized materials development with the limited available budget until end of 2018.
- Down-selection of advanced steel options
- Down-selection of HHFM options
- Further populating the Materials Database and finalising Materials Handbooks (Tungsten Alloys, CuCrZr)

The main impact to WPMAT arising from the roadmap update:

EDDI (budget increase 100%)

- Design rules have to be finalised and verified. This requires a much higher effort in materials testing including a high number of complex and expensive test procedures. → Material Test Institutions have to be included in the work programme.
- The baseline materials data have to be prepared to be included in Nuclear Codes and Standards. → Support of industrial experts is required.

HHFM (budget increase 50%)

- The current activities related to the DEMO diverter will have to be continued.
- Successful approaches have to be investigated on an industrial scale. That requires large-scale production of advanced materials and demonstration of industrial technologies (e.g. densification, pipe extrusion, bending, bonding, shaping, sintering, etc.). This step requires massive involvement of industry.

AS

- The current activities related to DEMO blanket structural applications need to be continued.
- Large-scale industrial production of at least three steel types in the range of several tons is required.
- Budget increase of 1-2 Mio. € per batch, that is about 5 Mio. €

FM

- The current activities related to optical & di-electrical materials will have to be continued. This will lead to several commercially produced ceramics with reproducible properties.
- Low dose neutron irradiations are required for their characterisation.
- Budget increase of 200 k€ per year depending on available irradiation procedures.

IREMEV

- The current activities in support of the material development activities have to be continued.
- Additional topics like He embrittlement, PMI and T retention/release have to be started.
- More focus has to be laid on validation and the exploration of experimental techniques as an alternative for neutron irradiation. This involves also micro/nano-scale testing techniques.
- Staffs increase of about 5-8 ppy.
- Budget increase depending on availability of facilities.

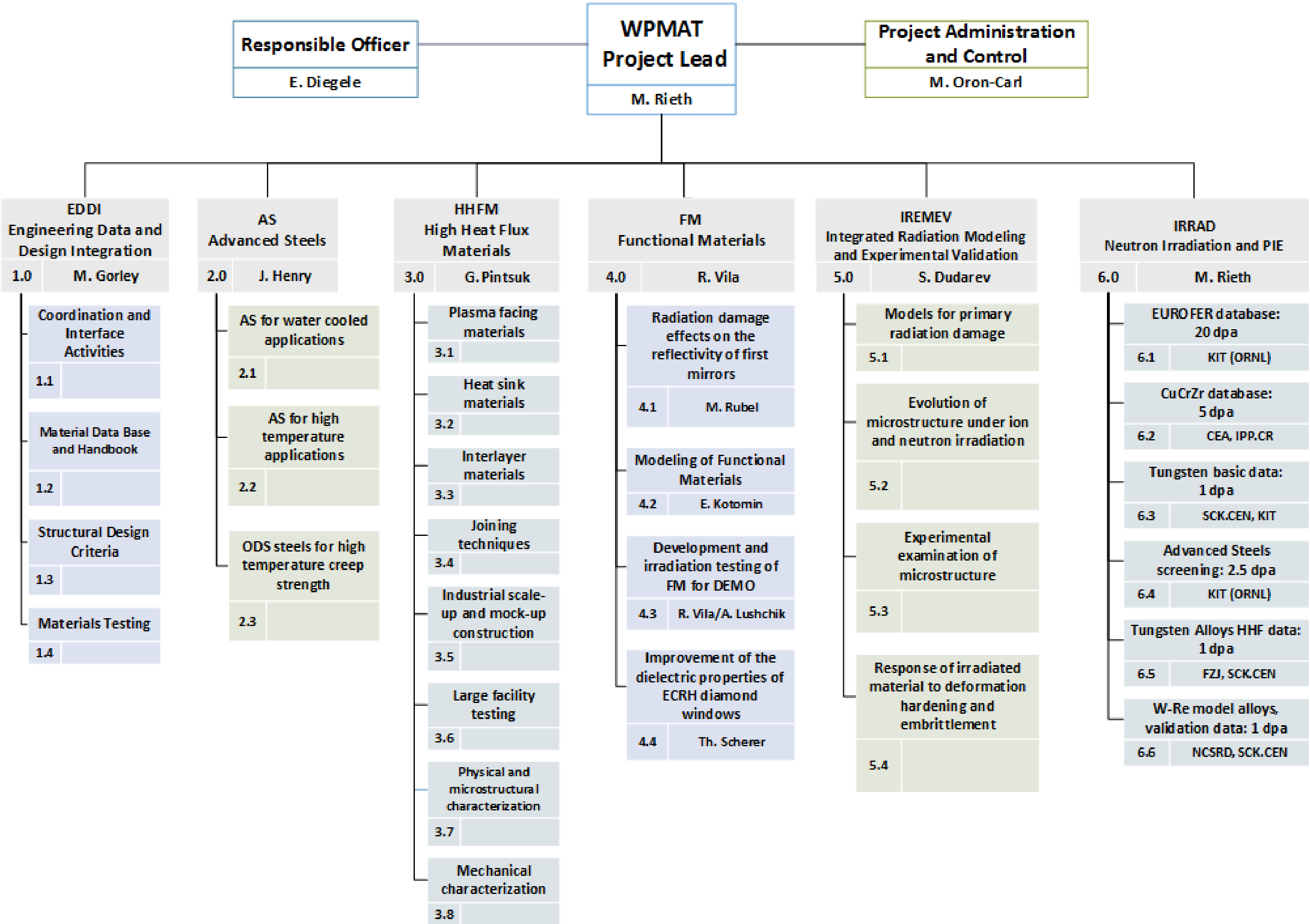
IRRAD

- Neutron irradiation campaigns will require about 8 Mio. € per year for the near future, that is at least until DONES is well into operation. Without a continuous underlying irradiation program using most of the available MTRs worldwide, the ROADMAP to DEMO cannot be realised.
- It is also clear, that irradiation of base line materials, in particular, have to be considered as “nuclear services” and require an appropriate funding rate for irradiation (increase to 100%). The same holds for PIE, if performed outside Europe, as well as for waste disposal.

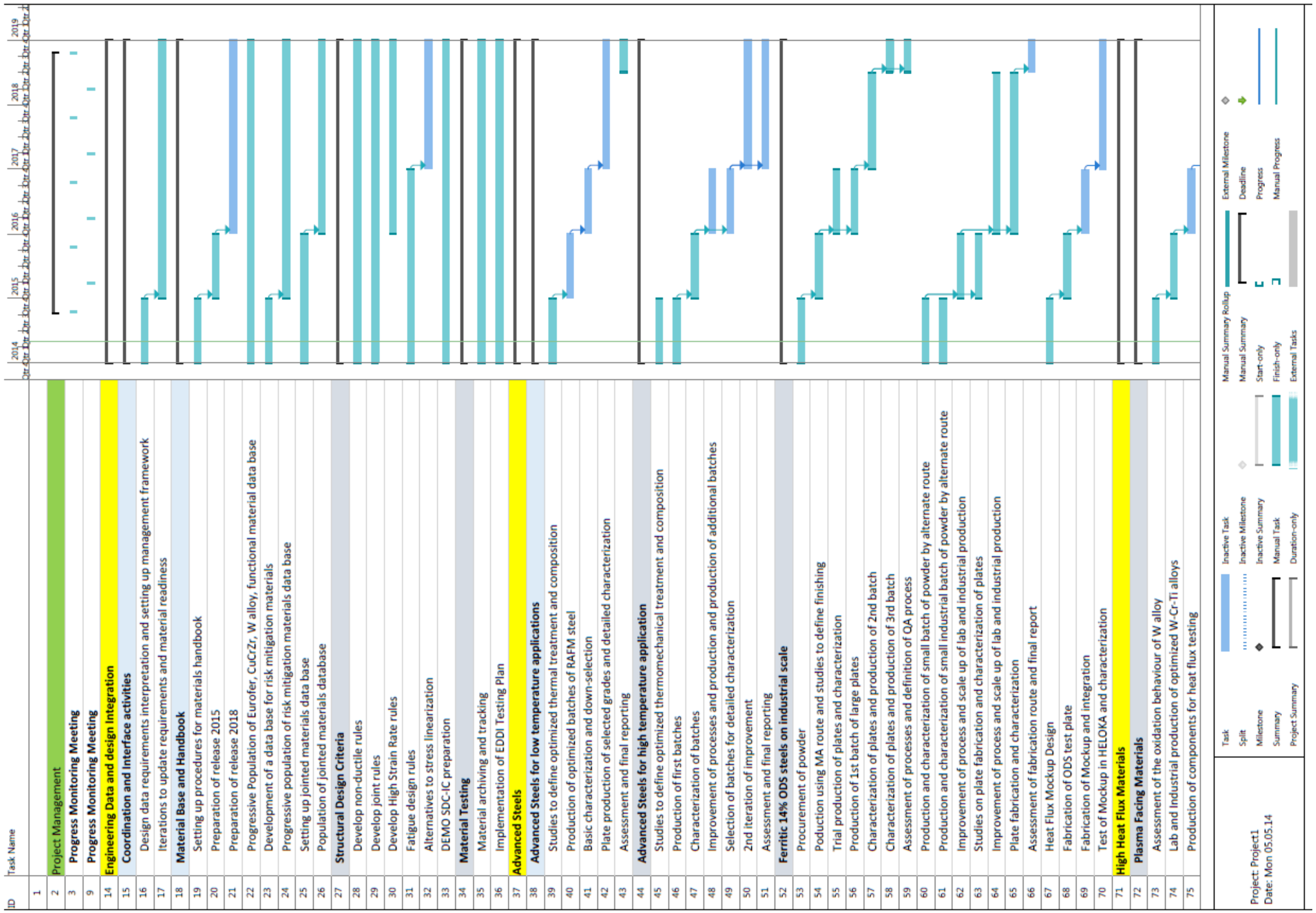
9. ANNEXES

Appendix A Work break-down structure
Appendix B Integrated Work Package schedule and key milestones
Appendix C Work Package deliverables status
Appendix D Progress against Project Grant Deliverables

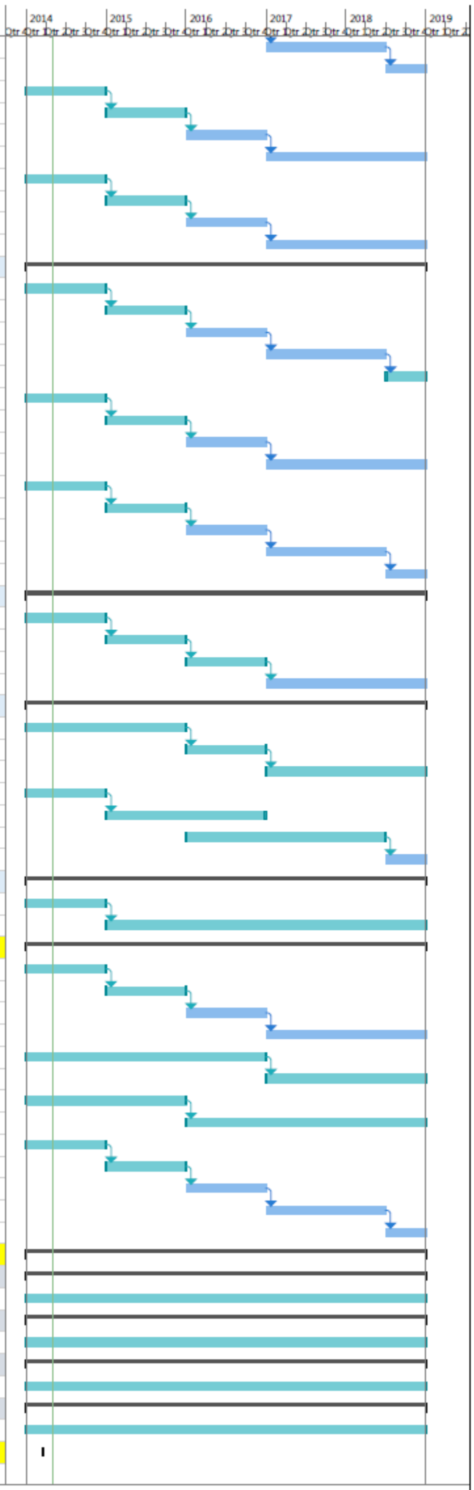
APPENDIX A: WORK BREAK-DOWN STRUCTURE



APPENDIX B: INTEGRATED WORK PACKAGE SCHEDULE AND KEY MILESTONES



ID	Task Name
76	Production of components for heat flux testing
77	Production of components for heat flux testing
78	Manufacturing of specimens for HHF testing by PIM route
79	Optimization of process
80	Development of PIM tool for real-size armor monoblocks
81	Production of real-size armor parts
82	Development of SiC/W based composites
83	Fabrication and testing of composite samples
84	Improvement of the W-based matrix samples and downseletion of materials
85	Manufacturing and characterization of larger dimensions composites
86	**High Heat Flux Materials**
87	Assessment of industrial production routes for W/Cu, W/Cr, W(f)/Cu
88	Fabrication and characterization of hot extruded pipe following concept I
89	Fabrication and characterization of hot extruded pipe following concept II
90	2 m prototype pipe fabrication and assessment
91	Assessment of the industrial manufacturing process
92	Fabrication of W-laminates with Cu and V interlayers
93	Assessment of W-multi metal laminates
94	Establishing the pipe fabrication route by HRP
95	Fabrication of medium-scale mockups for HHF testing
96	Setting up the routes for W-fiber reinforced W
97	Sample manufacturing and characterization of samples following PM and CVI route
98	Large scale CVI route
99	Large scale PM route
100	Assessment of fabrication routes
101	**Interlayer Materials**
102	SPS assemblies of W/CuCrZr with W/Cu interlayers
103	Characterization of assemblies
104	Development of PM route for FMGs and SPS route for mockup fabrication
105	Medium scale and industrial scale mockups fabrication and assessment
106	**Joining Techniques**
107	Development of joining process by electrodeposition
108	Characterization of joints
109	Fabrication and testing of mockups of electrochemically deposited joints
110	Development of new brazes
111	Production of samples and characterization
112	Technology development for Cu-C based materials
113	Fabrication of large tapes
114	**Scale-up, Mockup Construction and Testing**
115	Setting up new DEMO HRP, KATHELO, GLADIS, JUDITH and definition of testing procedures
116	Mockup Manufacturing and HHF, thermal shock and thermal fatigue tests
117	**Functional Materials**
118	Development and characterization of self-doped alumina
119	Development and characterization of Spinel structure materials
120	Irradiation of Materials and assessment of radiation damage
121	Study of advanced processing routes for functional materials
122	Modelling of damage in alumina
123	Modelling of damage in silica
124	Production and characterization of Mo mirrors
125	Production and characterization of new mirrors
126	Procurement and tests of (diamond) windows
127	Studies to reduce losses
128	Brazing studies for windows
129	Passivation studies of diamond windows
130	Modelling of loss mechanisms
131	**IREMEV**
132	**Models for primary radiation damage**
133	Studies to improve radiation damage description beyond the dpa concept
134	**Evolution of microstructure under ion and neutron irradiation**
135	Development of models of microstructure evolution, segregation and precipitation
136	**Experimental examination of microstructure**
137	Defect and dislocation analyses to develop correlation beween microstructure and
138	**Response of irradiated materials to deformation: hardening and embrittlement**
139	Studies on interaction radiation defects with dislocations
140	**Neutron Irradiation**
141	to be worked-out



Project: Project1
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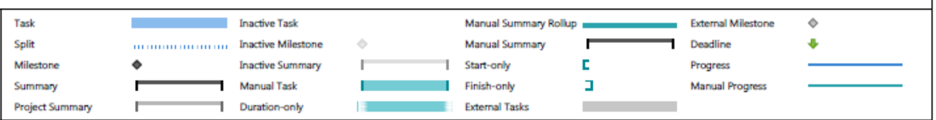
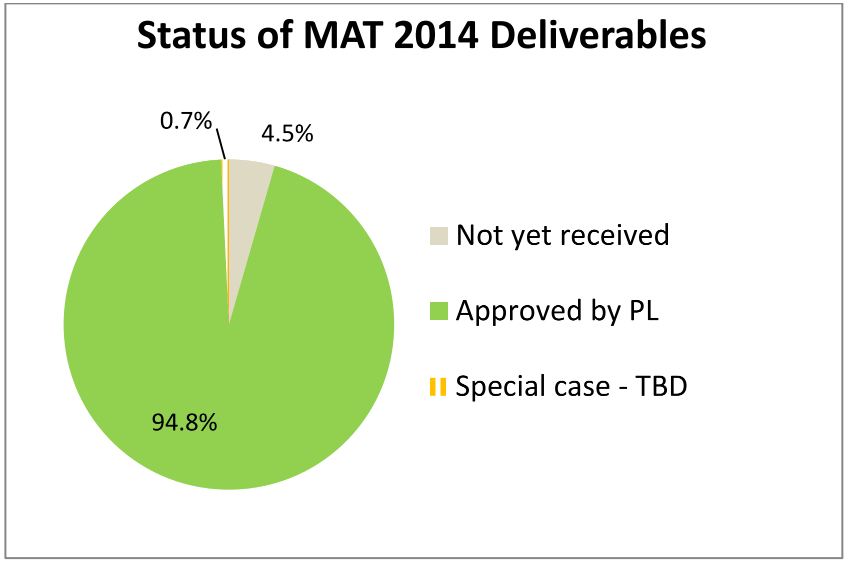
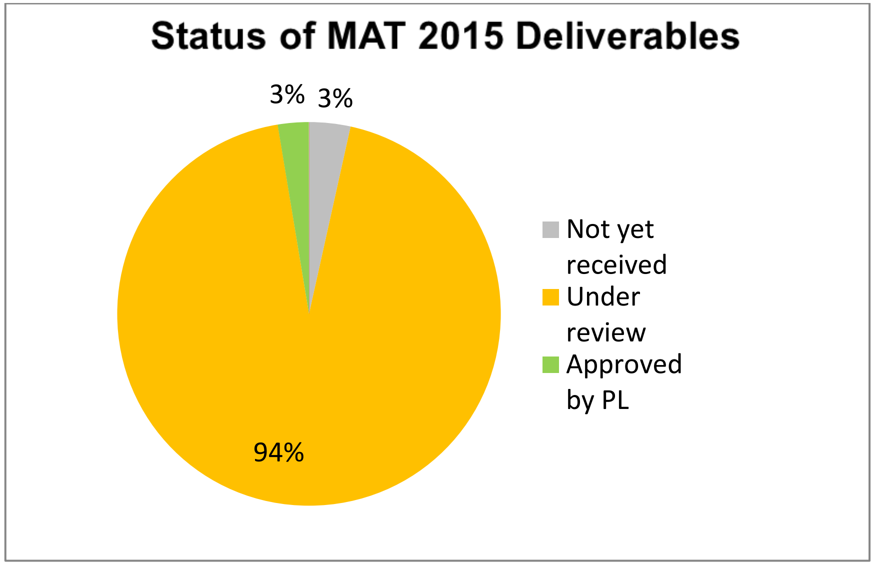


APPENDIX C: WORK PACKAGE DELIVERABLES STATUS (2014, 2015 AS OF 13TH APRIL 2016)





APPENDIX D: PROGRESS AGAINST PROJECT GRANT DELIVERABLES

Del. Title	Due date	Status after Q2	Explain/describe difficulties**	Corrective actions/Proposed measures**
MAT.D02.1 Adv. Steels and HHFC baseline material development, trial heats & screening test	Dec-14			
MAT.D02.2 Adv. Steels and HHFC risk mitigation material development, trial heats & screening test	Dec-15			
MAT.D02.3 Adv. Steels and HHFC - baseline material production and characterisation - first batch	Dec-15			
MAT.D03.1 Reports on R&D, performance demonstration of key technologies, manufacturing feasibility, etc. (1st formal release)	Dec-15			
MAT.D06.1 Materials Properties Handbook: (1st formal release)	Dec-14			
MAT.D06.2 Materials Properties Handbook: (2nd formal release)	Dec-15		delay by 15 month	none
MAT.D07.1a Materials modelling and validation: (1st formal release)	Jun-15			