REVISED DEMO DESIGN AND DEVELOPMENT PLAN

As part of the update of the EU Roadmap to Fusion Electricity.

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IDM Reference: 2N2FJB

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EXECUTIVE SUMMARY

Following the ITER revised schedule, which, however not yet formally accepted, now sets as a date of first-plasma with several years delay with respect to the previous plans, it has been decided to update the Roadmap to Fusion Electricity [1] to explore possible adaptations to be implemented to minimise the impact of the ITER delay on the demonstration of fusion electricity generation in a Demonstration Fusion Power Reactor (DEMO) around the middle of the century. This document is a revision of the DEMO design schedule and design approach, which forms part of the update to the European Fusion Roadmap. Priorities on technology R&D defined in the original roadmap document are all confirmed and are not discussed here. An update on the strategy for the development and qualification of DEMO Structural and High-Heat Flux Materials is described elsewhere [2]]. The physics R&D, related to the development of DEMO relevant plasma operating scenarios, and integrated solutions to the problem of power exhaust are described in detail elsewhere (see [3]]. [4]])

The proposed strategy for the DEMO design and R&D is oriented along the core mission to develop fusion as an attractive energy source to which funding for fusion R&D is intrinsically linked and keeps the date of demonstration of fusion electricity to the grid in the 2050's. The many uncertainties inherent in fusion physics and technology, and the delay of ITER D-T operation complicate the issue of DEMO design and delivery. A timeline for the pre-conceptual, conceptual, and engineering design of DEMO is presented, with the following features:

- **Pre-conceptual design:** Multiple plant design concepts assessed in parallel, and compared against a reference concept (referred to as the "baseline"). Emphasis should be on engineering and operational challenges, safety, power conversion aspects and reliability of the power plant. This phase culminates in the selection of a concept with the highest likelihood of success (the baseline at the time of down-selection) by the end of 2020, and potentially one back-up alternative design for risk mitigation and exploitation of potential opportunities (e.g. enabling technology dependent).
- **Conceptual design:** The selected architectures are taken in the conceptual design phase and further assessed and compared, with a single architecture (still with sub-variants) is selected in the mid 2020's, in preparation for a concept design review by 2027.
- **Engineering design:** The selected DEMO architecture enters the engineering design phase where system level solutions are progressively selected and substantiated with detailed engineering assessments and technology R&D, including prototype testing of the major components/systems to confirm and optimise their operational use, working towards the selection of a site and the start of construction around 2040.

1 INTRODUCTION

The objective of this document is to describe the main aspects of the proposed revision to the DEMO design schedule. Section 1 provides the background and defines the objective and scope of this document. Sections 2 and 3 describes the revised DEMO conceptual design approach and schedule, respectively, which have been developed taking into account the delay foreseen for the end of construction of the ITER project, and the need to demonstrate fusion electricity around the middle of this century. Section 4 introduces a proposed systems engineering approach for the assessment of design options (i.e., optioneering[1]); defining the drivers and issues that need to be addressed in order to enable decision-making against a range of attributes.

1.1 Background

As an important part of the Roadmap to Fusion Electricity [1], Europe is now, within Horizon 2020, conducting an initial conceptual design study of a Demonstration Fusion Power Plant (DEMO), i.e., a reactor design capable of demonstrating net production of electricity and operation with a closed fuel-cycle and to be the single step between ITER and a commercial reactor. At present, the DEMO reactor design has not been formally selected and detailed operational requirements are not yet available. Where exactly DEMO should be located in between ITER and a commercial fusion power plant depends on the remaining gaps towards a commercial plant after the exploitation of ITER, and the time scale for fusion deployment and development risks that can be accepted. It will be an important task of the pre-conceptual design activities to assess and outline an achievable location[2] consistent with the Roadmap timeline and allocated budget.

Since the initial publication of the European Fusion Roadmap, considerable progress has been made in the understanding of the DEMO challenge. The conceptualization of DEMO represents a truly first of a kind endeavour with unprecedented complexity in the diverse interdependencies inherent in this next generation tokamak, where the outcomes are not entirely determinable. “First of a kind” endeavours are, as the name suggests, pioneering and must accommodate uncertainty, discovery of unforeseen outcomes, and consequently improved understanding. This requires a carefully considered approach with a deep understanding of the design drivers and their influence on the key plant features which will be used to compare competing variants.

1.2 Organisation

Precursory work was conducted in 2011-2013 as part of the EFDA Power Plant Physics and Technology (PPPT) programme with a focus on: (i) the identification of the DEMO pre-requisites; (ii) the main design and technical challenges (physics and technology); (iii) the preliminary assessment of the foreseeable technical solutions; and (iv) the prioritization of R&D activities to be launched as part of the new EU fusion roadmap.

The execution of the DEMO design work now being done in the PPPT Department of the EUROfusion Consortium is distributed across many geographically dispersed teams (see Fig. 1) with defined scopes, deliverables, milestones, time schedules, and resource allocation. The core PPPT team in the Programme Management Unit (PMU) is responsible for Programme Coordination and Control, and Design and Physics Integration. As the PPPT team is relatively small in size, a number of Systems Engineering, Design Integration, and Physics Integration tasks are outsourced annually to the wider EUROfusion Consortium members, through the work package WPPMI. This approach is

[1] Optioneering is a structured evaluation of options in support of decision-making. Such an evaluation may take the form of an Option Study that collates information on the options and the different attributes that will influence the decision to be made and may also consider how the decision is influenced by different value judgements.

[2] The need to establish realistic target performance and a development schedule for near-term electricity demonstration tends to favour more conservative technology choices. The readiness of the technical (physics and technology) assumptions that are being made is also expected to be an important factor for the selection of the technical features of the device.

complex and requires an adequate strategy for communication and co-ordination of design integration activities, including training and adherence to procedures.

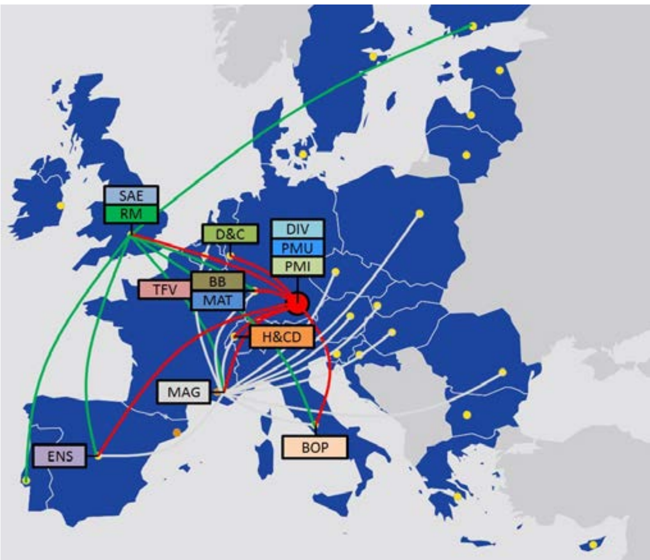


Figure 1: Organisation of Design and R&D Activities. **WPBB:** Breeding Blanket project; **WPBOP:** Heat transfer, Balance-of-Plant and Site project; **WPDC:** Diagnostic and Control project; **WPDIV:** Divertor project; **WPHCD:** Heating and Current Drive systems project **;** **WPMAG:** Magnets System project; **WPMAT:** Materials project **WPPMI:** Project Management, Design and Physics Integration tasks; **WPRM:** Remote Maintenance System project**;** **WPSAE:** Safety and Environment project**;** **WPTFV:** Tritium, Fuelling & Vacuum systems project**;** **WPENS:** Early Neutron Source project**;** **WPCS:** Containment Structures project. In the scheme the composition of the project teams of WPRM and WPMAG are also shown.

1.3 Setting the DEMO ambition

To ensure timely delivery of the Fusion Roadmap objectives and to ensure that the work conducted is valuable to the eventual adopters of the technology, EUROfusion has engaged a DEMO Stakeholder Group, consisting of experts (e.g., industry, utilities, grids, safety, licensing, etc.), to establish a set of realistic high level requirements for the DEMO plant, in order to embark on a self-consistent conceptual design approach [5]. This shall ensure that the Stakeholders' perspectives are captured during the initial identification of leading technologies, and the eventual down-selection for the most promising design options.

To make prudent choices concerning the future path of fusion power, one should draw important lessons from the fission experience of developing and deploying nuclear reactors through successive generations. The fission evolution has been catalysed by the need for advances in safety, materials, technology, and commercial attractiveness – in addition to the strong involvement of industry from the beginning. In order to better steer the DEMO ambition, a number of meetings were held with managers of advanced Gen-IV Fission projects ASTRID and MYRRHA who have provided very valuable advice and observations (see Annex 7.1).

1.4 Framing the Programme envelope

1.4.1 Delivery considerations

Different types of new fission plants are being developed today that are generally referred to as advanced reactors. In general, an advanced plant design is a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced reactors consist of evolutionary designs[3] and innovative designs[4] requiring substantial development efforts. The latter are more ambitious and differ from evolutionary designs in that a prototype or a demonstration plant is required. In contrast to fission, where the benchmark design point is represented by existing operating plants (mostly Gen II) with very high availability, there will very likely be only a few representative nuclear fusion plants that will exist in the next thirty years; i.e., ITER and the Chinese Fusion Engineering Test Reactor (CFETR) [6].

Where DEMO is positioned between ITER and a commercial fusion power plant (FPP) remains to be determined; it is dependent on the gaps to commercialisation after the exploitation of ITER, and the acceptable time scale, risks, and costs for fusion deployment. It will be a task of the pre-conceptual and conceptual design activities to determine this location, by minimising feasibility risks and costs of the identified best technical solutions for a DEMO plant. It is important to note another factor that should be considered in the positioning of the DEMO Engineering Design Activity (EDA) phase with respect to ITER; an entire generation of engineers will have brought ITER to fruition, and if the DEMO EDA starts too long after ITER is delivered this highly skilled and experienced workforce will be lost to other industries. Similarly, a large gap from the end of the construction and assembly of ITER (noting that the manufacturing of some of the components/ systems are expected to be completed well in advance of start of DT operation) to the Engineering Phase of DEMO would lead to the loss of industrial interest and expertise.

In particular, the definition of the technical characteristics and required “economic” performance of a commercial FPP is currently very challenging, considering that the commercial penetration of fusion power is not expected to happen before the second half of the century. Setting attractive thresholds of economical attractiveness or competitiveness with other sources is difficult, because of the large uncertainties associated with the commercial landscape of the energy market at the time a decision on an FPP is to be made. Moreover, the impact those geopolitical and environmental factors may have on the development path of long-term energy solutions, together with the associated regulatory challenges in the licensing of new nuclear plants are very difficult to predict.

The pure economics of an FPP may well not be the only driving force behind the desire to realize one. The future value of the promise of plentiful fuel, further evidence on climate change, the geo-political situation of entities that would potentially invest in such a device, and the social acceptability of other sources of energy will all have a bearing on what an FPP needs to achieve to be attractive. Safety is also expected to have a strong impact on design, so it is essential in the DEMO conceptual design activities that safety considerations lie at the heart of design choices from the very beginning.

Thoughts are being given on how to develop a credible fusion development strategy to position DEMO in order not to preclude the important - albeit ambitious - goal to enable (at least during the later phase of operation) an acceptable extrapolation from DEMO to a First-of-a-kind Fusion Power Plant. Appendix 7.2 outlines for example a so-called stepladder approach that considers solely from the point of view of plasma physics a sequence of self-consistent feasible designs for ITER/ DEMO and a FPP. It should be noted though, that the validity of this approach requires the confirmation of an equivalent technology development path that traditionally follows instead a more incremental technology readiness step-based approach, where advances of each subsequent steps are driven by advances in safety, materials, technology and commercial attractiveness in addition to strong involvement of industry from the beginning.

[3] *Evolutionary design* - is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. The development of an evolutionary design requires at most engineering and confirmatory testing.

[4] *Innovative design* **-** is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and a prototype or demonstration plant are probably required.

In this context, the intention is to exploit industrial experience directly by means of individual subtasks to be contracted to companies with experience in designing and building nuclear devices and plants. It is hoped that by including such industrial partners, the programme will benefit from their nuclear engineering expertise, their skills to assess technical feasibilities, and a general awareness of licencing issues and other risks. Appropriate companies will be contracted for limited and well-defined subtasks but these collaborations will provide the basis to discuss and share industrial views, analyses, and understanding – applying them to other tasks, where relevant.

1.4.2 External constraints

Furthermore, it is important to highlight some key external constraints which have the potential to affect the delivery of the Programme objectives, and the positioning of DEMO in relation to ITER and a commercial FPP.

1.4.2.1 ITER's successful operation is a prerequisite for completion of DEMO design

DEMO can only be built once the validity of its operational scenario is verified and confirmed by global plasma and machine performance and operation at Q=10 (e.g., confinement, density, pedestal, self-heating for alpha-particle. Lessons learned from the initial operation of ITER will include both essential information on plasma performance (confinement/burn, current drive/steady-state, disruption control, edge control, etc.), and engineering feasibility/ component performance/infant mortality of plasma support systems (fuelling, H&CD systems, divertor, etc.).

Whilst the importance of information obtained from the operation of ITER cannot be overstated, it is crucial that the DEMO design schedule is robust to further changes in the ITER schedule and also takes into account other machines that are either under construction or being considered for construction (e.g. JT-60SA [7], CFETR [6], the Divertor Test Tokamak (DTT) Facility [8], etc.) which have the potential to play a role in reducing uncertainties (both in physics and technology) for DEMO.

1.4.2.2 Political constraints

It is felt that in order to justify the continued use of public funds to develop nuclear fusion to the point of electricity production, there must be an emphasis on a solution that allows fast deployment of fusion energy. A tangible and realistic goal for the delivery of fusion electricity to the grid must be kept, in order to maintain the momentum behind fusion R&D, and not to lose track of the very real need for cheap, safe, and carbon neutral electricity production in the latter half of the 21^{st} century. Postponing the presently targeted delivery date by more than a decade bears the risk of loss of public and political interest in fusion as a solution for the world's future energy needs; associated reduction in funding would be a logical next step, and would run the risk of delaying fusion electricity well into the 22^{nd} century.

1.4.2.3 Availability of tritium supply

Tritium supply considerations are very important for defining the implementation timeline of a DEMO device, which must breed tritium from the very beginning and use significant amount of tritium (5-10 kg) for start-up. tritium decays at a rate of 5.47 %/yr. Current realistic forecast of civilian tritium supplies available in the future points to very limited quantities of tritium available after ITER operation and in view of the limits above to start-up only one DEMO reactor this must operate and produce its own tritium around 2050 at the latest [9,10,11]. Increasing supplies of tritium is clearly a controversial topic that lies outside of the fusion community's strategical control. Options include, for example: (i) extending the life of Canadian and South Korean CANDU reactors well beyond 2030; (ii) building new tritium-producing facilities (dedicated or otherwise). Other options, like D-D start-up are being considered [12], but implications on design and operation hurdles are still unclear and further work is progress to assess the attractiveness of this proposal. Furthermore, the construction of any intermediate fusion device with a net tritium consumption in any part of the world during the next two decades (e.g., Chinese Fusion Engineering Test Reactor (CFETR) in China [6]) will further limit the availability of the tritium supply.

2 DESIGN APPROACH

In 2014, a traceable design process with a Systems Engineering approach was started to explore the available DEMO design/operation space, and to understand implications on technology requirements and plasma physics basis development needs. The main challenges include:

- Design dealing with uncertainties (physics and technology) and their propagation;
- High degree of system integration/ complexity/ system interdependencies;
- Trade-off studies with multi-criteria optimisations, including engineering assessments;
- Non trivial qualification route to improving technology maturity, mindful of their inherent risks.

As an important part of the update to the Roadmap, in view of the many uncertainties still involved and recognizing the role of DEMO in fusion development, it is judged undesirable for the initial study effort to focus solely on developing the details of a single design point, since there is the need to keep flexibility in the approach. It is proposed to expand the effort to explore the wider DEMO design space. A pulsed “low extrapolation” system based as far as possible on the ITER Q=10 scenario, mature technologies, reasonable confidence in the regimes of operation, and material selection for the expected level of neutron fluence will form the baseline. In parallel we want to examine a number of alternative DEMO architectures and their sub-variants so that a well-informed assessment of options, driven by a rigorous systems engineering approach and plant assessment criteria, can be carried out. The rationale and the proposed strategy for the evaluation of alternative plant architectures are elaborated in Section 4.

The purpose of these alternative architecture studies is twofold. First, they should be defined to cover a wider solution space and stimulate the development of alternatives which perform better against the plant assessment criteria. In particular these should address major uncertainties and shortcomings identified in the baseline (e.g., improved concept of power exhaust and associated first wall protection strategy - recognised to be one of the most crucial interfaces for the design and development of fusion power systems), or investigate upfront potential showstoppers linked to the adoption of specific design choices affecting safety and/or the overall plant layout and operation. Second, they should include assessments of attractive DEMO plant options that differ substantially from the point of view of readiness of the technical assumptions being made in plasma physics and technology and evaluate, with the support of industry their feasibility issues, technical readiness level, associated development risks, and development cost and schedule. These will define plasma physics scenarios to be studied in ITER that differ from the present Q=10 scenario, such as the Q=5 steady state option.

Concept selection criteria have to be developed and implemented that need to be harmonized with the Systems Engineering processes under development in the PMU. Safety is also expected to have a strong impact on design, so it is essential that safety considerations lie at the heart of design choices in the DEMO conceptual design from the very beginning.

3 REVISED DEMO DESIGN SCHEDULE

3.1 Design phase evolution

This section aims to characterise the pre-conceptual and conceptual design phases, and in particular, how the programme must strike a balance between the need to focus on delivering the objective of a self-consistent baseline and associated deliverables, on one hand, whilst exploring the design space and remaining flexible to alternative concepts or technologies that offer attractive solutions on the other.

ITER is a crucial step and its construction and operation will provide major advances in technology and physics knowledge. Nevertheless, outstanding physics and engineering challenges will remain in some areas with potentially large gaps beyond ITER that need to be overcome and that require a pragmatic approach. They include, for example, the selection of: (i) the plasma operating scenario; (ii) the breeding blanket concept and, in particular, the selection of blanket coolant and the BoP; (iii) the divertor concept and layout configuration; (iv) the first-wall design and integration to the blanket (mechanical and hydraulic), taking into account that the first-wall might see higher heat loads than assumed in previous studies; (v) the H&CD mix; and (vi) the remote maintenance scheme.

The impact on the overall plant reliability and availability of the various system design options must be analysed in an integrated approach taking into account that there are strong interdependencies. Emphasis should be on engineering and operational challenges, safety, and power conversion aspects of the power plant.

Key decisions that are expected to be made in advance of the end of the conceptual design phase include:

- Divertor configuration selection and first wall protection strategy (SN/DN)
- Breeding blanket concept and coolant selection
- Plasma operating scenario selection
- H&CD mix selection

These are needed to enable resources and activities to be focussed on the preparation of a sound plant concept design in advance of the conceptual Plant Design Review (PDR) (see Section 3.1.2 and Annex 7.3).

3.1.1 Pre-conceptual design phase

The pre-conceptual design phase describes the period after a set of high level stakeholder requirements are agreed upon, where several candidate plant options are developed and specified. At this stage, each of the options must be sufficiently developed to enable meaningful comparisons, paving the way for assessment criteria to be applied when making decisions on the DEMO plant options. Throughout this phase, and continuing into the conceptual design activity (CDA), there is a "baseline" DEMO plant option, which serves as a concrete example for studying the complex interlinks between the different areas. Study of the baseline enables the more concrete and detailed design studies to be carried out, including integration aspects (often critical in tokamak design), many of which are relevant for multiple plant options. Nevertheless, the possibility must be maintained throughout the CDA phase to switch the baseline configuration to one of the alternative options if it becomes more feasible than the initial baseline configuration. R&D must be coordinated in order to drive these alternative options in the direction of decreasing technical gaps.

Hence, the baseline may change at any point, following a comprehensive comparison with the concurrent alternatives. With the above understanding, within the pre-conceptual design phase, the opportunity remains to make fundamental modifications to the baseline plant concept, *if* an alternative concept can be demonstrated to significantly increase the probability of meeting high-level requirements and/or significantly reduce technical or programmatic risks. Similarly, if it becomes apparent during the pre-conceptual design stage that any one of the plant concepts is unfeasible, or its performance does not meet the high level requirements, its development shall be terminated so that resources may be focused elsewhere (see Figure 2).

At the end of the pre-conceptual design phase, the number of DEMO plant candidates will be narrowed down to the concept with the highest likelihood of success (the baseline at the time of down-selection), and potentially one back-up alternative architecture, for risk mitigation and exploitation of potential opportunities (e.g. enabling technology dependent). Each of these two architectures carried forwards may have some very limited sub-variants relating to system-level solutions. An objective and rigorous assessment framework that can differentiate between the attractiveness of plant concepts is required to support this approach. This framework shall *inform* decisions on whether to modify the baseline; taking full account of the programmatic implications. The application of this framework to assess plant options at the pre-conceptual stage will pave the way for the down-selection of system-level solutions as the programme progresses towards the conceptual phase. The main lines of this evaluation framework are introduced in Section 4 of this document.

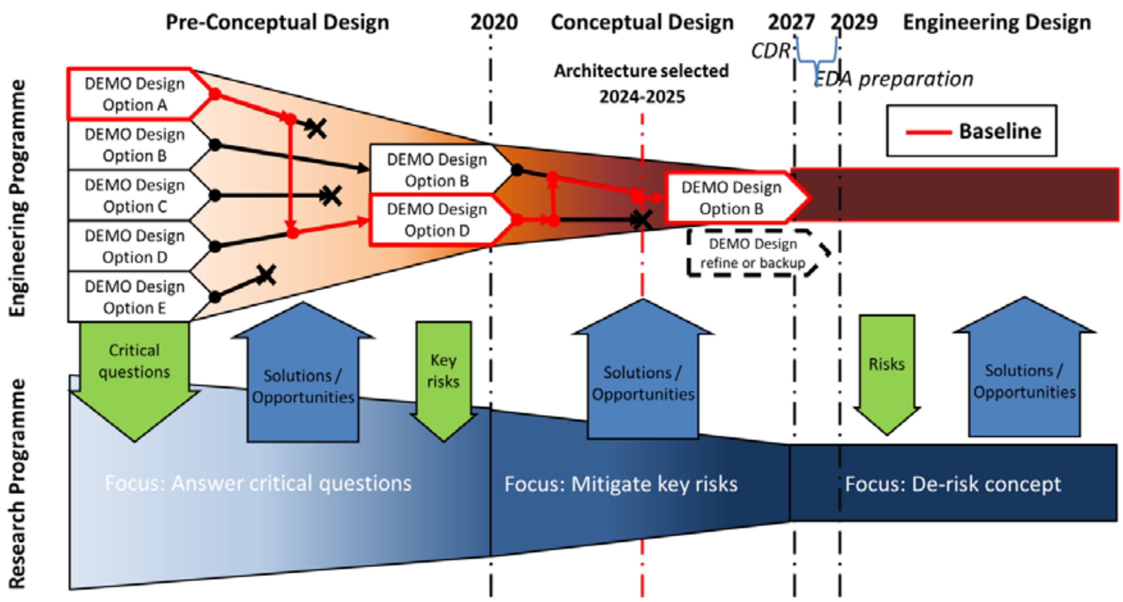


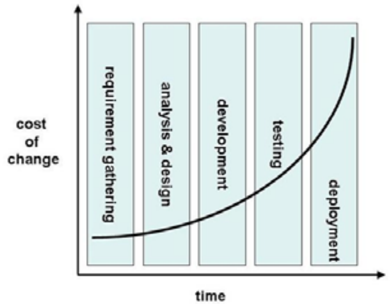
Figure 2: Development of the DEMO design options and associated R&D activities through the pre-conceptual, conceptual, and engineering design phases

3.1.2 Conceptual design phase

The evolution from a pre-conceptual design to a conceptual design is required to bring the plant design concept to a complete integrated system where feasibility, safety and licensing issues and costs, including development cost and times to be expected during the subsequent engineering design phase must be determined. This is typically a very critical phase in a project as authorization of project funding expected to continue its lifecycle (i.e., entering an engineering design phase), is subject to the successful completion of the conceptual design work and passing the Plant Design Review (PDR). As indicated in Figure 2, the architecture of the DEMO plant should be selected two to three years in advance of the PDR, to enable resources and activities to be focussed on the preparation of the concept to be presented. A tentative list of deliverables foreseen for the conceptual design phase is shown in Annex 7.3.

This stage includes the continuing development of improved design solutions and technology improvements required to increase the maturity of the initial design work, including interfaces between the system and its intended environment, and a comprehensive evaluation and minimisation of the cost, safety and feasibility. R&D work during this phase is expected to aim predominantly at the validation and readiness work to establish sufficient confidence that most of the design and technology solutions adopted are feasible. Large scale demonstration R&D and testing are mainly foreseen during the EDA phase. Nevertheless, some initial manufacturing tests or system component performance tests are required at prototype scale even during the CDA phase. In particular, the remote maintenance strategy is pivotal in the definition of much of the physical layout of the in-vessel components, vacuum vessel and magnets. As there are strong implications on reactor design, it is important that the proposed remote maintenance strategy for the servicing of the in-vessel component is confirmed through test-rig and trial demonstrations during the concept design phase.

Postponing this initial demonstration work to a later stage would increase the risks of arriving to a plant design concept with still significant development uncertainties and risks. System level solutions upon which the DEMO architecture is dependent should be validated to an extent during the conceptual design phase, to mitigate the risks of significant overhaul during the engineering design activities. The importance of getting the requirements and the initial design and analysis right at the very beginning of a project is illustrated in Figure 3.



	systems cost factors
requirements	1x
design	3-8x
build	7-16x
test	21-78x
operations	29-1615x

Figure 3: The costs of change to a system increase significantly past the pre-conceptual design phase (requirements capture and preliminary design studies). [13]

3.1.3 Engineering design phase

The DEMO design must be supported by extensive technology R&D during this phase in order to de-risk and validate key aspects of the design, including development and qualification of all the applicable technologies and development and verification of industrial level manufacturing techniques with related quality assurance. This includes prototype testing of the major components/systems to confirm and optimise to the best extent possible their operational use. Major design developments, fabrication, and tests are expected during the engineering design phase to: (i) validate the technologies incorporated in the DEMO design; (ii) confirm the manufacturing techniques and quality assurance; and (iii) support the manufacturing cost estimates for important cost drivers.

Similarly to what has been done in ITER with the so-called Seven Large R&D Projects (Central Solenoid Model Coil, Divert Cassette, Toroidal Field Model Coil, Blanket Module, Remote Handling, Vacuum Vessel Sector, Divertor, and Blanket Module Remote Handling) which cover all the major key components of the basic ITER machine and their maintenance tools, major developments and fabrication must be completed during this phase and testing of critical technology significantly progressed. The technical output from the R&D validates the technologies and confirms the manufacturing techniques and quality assurance incorporated in the ITER design, and supports the manufacturing cost estimates for important key cost drivers. Significant efforts and resources have been devoted to the Seven Large R&D Projects which cover all the major key components of the basic machine of ITER and their maintenance tools. The timely execution of these major programmes is vital during the EDA and the design is not expected to be frozen but to evolve to adapt to the responses of the R&D and the physic knowledge. This process is expected to continue until the start of ITER operation and validation of the operation scenario that is being used to design DEMO.

3.2 Revised DEMO design schedule

The schedule and key milestones for the DEMO design programme is shown in Figure 4. Emphasis is on the initial two phases described below:

- Phase 1: 2014-2020: Pre-conceptual Design
- Phase 2: 2021-2027: Conceptual Design
- Phase 3: 2028[5]-2040: Engineering Design Activity and Site Selection
- Phase 4: 2040-2050: Site Selection and Preparation (2035-2039) and Plant Construction

[5] A transition phase of about two years is expected for the concept design review consolidation and preparation of the Engineering Design Phase

- Phase 5: 2051-2054: Plant Commissioning
- Phase 6: >2054: Operation/ Demonstration of Electricity Production

ID	Task Name	Start	Finish
1	**DEMO**	**01.01.2014**	**01.01.2056**
2	**Pre-conceptual Design**	**01.01.2014**	**31.12.2020**
3	Plant Requirements Definition (1st baseline established)	19.03.2015	19.03.2015
4	**Conceptual Design**	**01.01.2021**	**31.12.2027**
5	Divertor Concept Selection	01.07.2024	01.07.2024
6	Breeding Blanket concept and coolant selection	01.07.2024	01.07.2024
7	Definition of DEMO operating scenario	01.07.2024	01.07.2024
8	DEMO conceptual Plant Design Review (PDR)	30.06.2027	30.06.2027
9	**Engineering Design**	**03.01.2028**	**31.12.2038**
10	PDR consolidation and preparation of EDA	03.01.2028	31.12.2029
11	Engineering design activity	01.01.2030	31.12.2038
12	Preliminary Design review	31.12.2034	31.12.2034
13	Operational feedback from ITER DT operation	31.12.2036	31.12.2036
14	Manufacturing Readiness Review	31.01.2037	31.01.2037
15	Request of construction licence (PCSR, Preconstruction safety report)	29.12.2038	29.12.2038
16	Final design review: decision to construct	29.12.2038	29.12.2038
17	**Site selection and preparation**	**01.01.2035**	**30.12.2039**
18	**Plant Construction Phase**	**03.01.2039**	**31.12.2050**
19	EDR consolidation and preparation of construction	03.01.2039	30.12.2039
20	Plant construction	02.01.2040	31.12.2050
21	TRR Test Readines Review	02.01.2045	02.01.2045
22	PCA Physical Configuration Audit	02.01.2045	02.01.2045
23	**Commissioning and operation**	**02.01.2051**	**31.12.2070**
24	**Commissioning**	**02.01.2051**	**31.12.2054**
25	Nuclear License for Operation	31.12.2054	31.12.2054
26	Plant acceptance review	31.12.2054	31.12.2054
27	**Operation**	**01.01.2055**	**31.12.2070**
28	Demonstration of electricity production	30.06.2055	30.06.2055

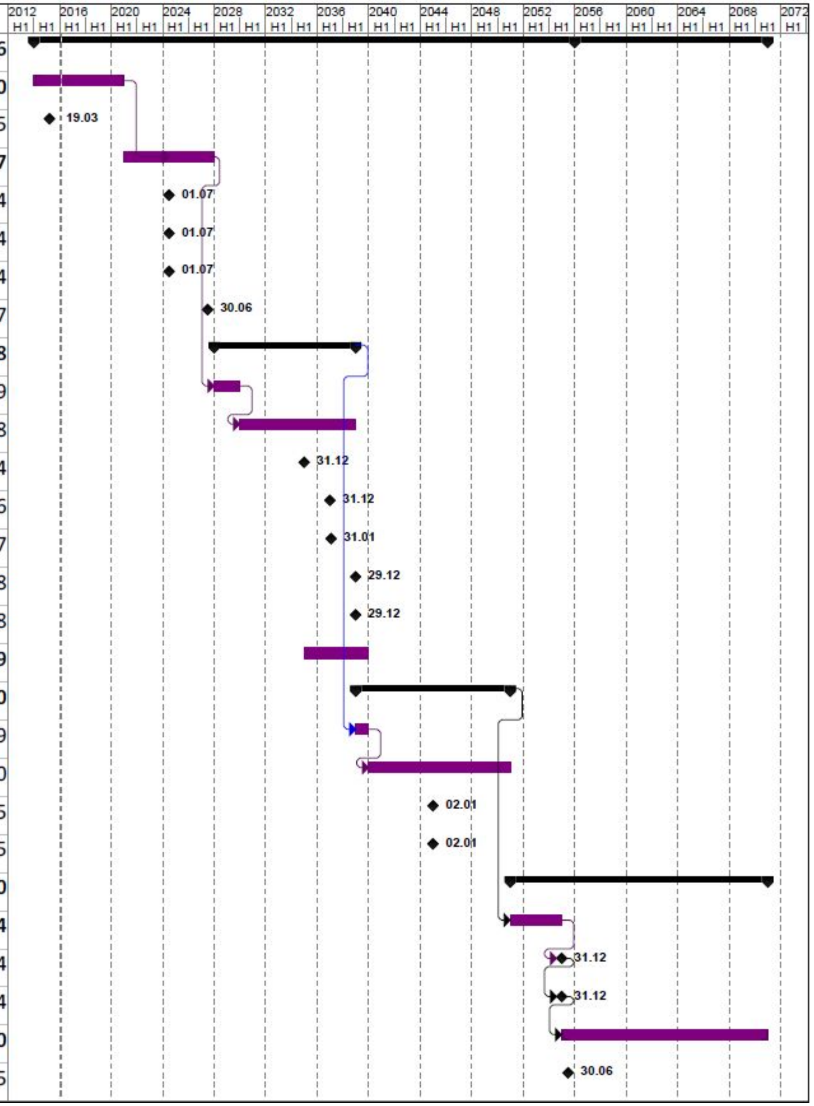


Figure 4: DEMO design schedule phases

PHASE 1 - PRE-CONCEPTUAL DESIGN (2014-2020)

- Capture lessons learned from current experiences within fusion and fission community.
- Engineering and safety policies and control through Systems Engineering management and supporting validation plans.
- Definition and analysis of initial requirements supported with a draft concept of operations.
- Preliminary design concept definition and trade-off analysis (up to 2018)
- Requirement trades, requirement definition review, trade and analysis review.
- Identify main physics basis development needs
- Determine critical technology development requirements (by involving more industry)
- Identify technology and material developments with high potential impacts on plant architecture and performance which can be concluded by Phase 2
- Conduct required technology and material R&D to fill gaps, aiming to achieve potential breakthroughs during Phase 2
- HAZOP, safety and ergonomic studies
- Key decision point: Concept evaluation and screening/selection of most promising plant architectures (one + back-up) with supporting system variants that meet the high level plant requirements, according to the best current knowledge.

PHASE 2 - CONCEPTUAL DESIGN (2020-2027)

Detailed concept definition and final trade-off analyses (2020-2024)

- Update lessons learned from latest nuclear community experiences, operational feedback from ITER, and relevant scientific developments.
- Materials qualification by analogous fission techniques linked with specific design code and standard development.
- Continue preliminary engineering of competing designs to a comparable level against agreed assessment criteria.
- Continue DEMO technology, material readiness and physics R&D through the technology management plan and consolidate results to fill the gaps with high impacts on plant architecture and performance (identified in Phase 1).

Key Decision Point: Critical assessment of key technical decisions to enable selection of a single conceptual design.

Finalisation of plant concept design and reviews (2024-27)

- Update lessons learned from latest nuclear community experiences, operational feedback from ITER/first materials data from fusion relevant environment, and relevant scientific developments.
- Preliminary Safety Report (PSR)
- Continue to progress the engineering design to increase the confidence in the front engineering design definition.
- Preliminary equipment, piping, instrument indices defining facility scope and classification of structures, systems and components.
- Preparation of a robust DEMO plant capital cost estimate, after a comprehensive cost optimisation exercise.
- Build cost, schedule estimates and project execution strategy for the next phase.
- Procurement and Contract strategy development for the next phase.

Key Decision Point: Review of Front End Engineering Definition (FEED) of DEMO plant concept for sanctioning to the next phase (see Section 7.3)

Concept plant design review consolidation and preparation of EDA phase (2027-29)

- Review and amend design solutions which did not pass the Conceptual Design Review
- Consolidate integrated plant conceptual design and resolve any outstanding critical issues

- Prepare EDA budget and detailed schedule
- Decision on whether to proceed to EDA
- Secure necessary funding
- Locate and procure site and facilities for a centralised DEMO Engineering Design Team

PHASE 3 - ENGINEERING DESIGN ACTIVITY AND SITE SELECTION (2030-2040)

- Operational feedback from ITER D-T Campaign assessing impact on Physics and Technology design basis.
- Material Qualification programme started
- Interim and detailed design reviews of all major systems and overall plant including supporting compliancy, constructability, maintainability, and operability assessments.
- Development of engineering design with staged release of Facilities, Materials & Equipment Requirements & Specifications.
- Concurrent R&D to de-risk technologies and system level solutions
- Operating Conditions and limits set including alarm / trip Settings (All plant states).
- Delivery/Construction schedule, and cost and resource budgets set. Installation procedures, Verification and Validation plans agreed
- Request of Construction Licence (sending of PCSR, Preconstruction Safety report)
- Final design review and engineering substantiation handover dossier drafted
- Decision to construct
- Site selection and preparation

PHASE 4 - SITE PREPARATION AND PLANT CONSTRUCTION PHASE (2040-2050)

- Procurement and expediting activities.
- Work control and management of vendors/contractors.
- Concurrent R&D to de-risk DEMO and applying change control.
- Equipment & Materials Catalogues
- As Built Data.
- Verification and Validation plan progress.
- Acceptance Test and inspection results.
- NCR closeout.
- Unfinished Work Details.
- Plant Certification.
- Spares Lists
- Operating and Maintenance Manual
- Handover Dossier
- Pre-commissioning safety report
- Test Readiness Review (TRR)
- Physical Configuration Audit (PCA)
- Commissioning schedule, cost and resources budgets set.
- Operations organisation appointment

PHASE 5 – PLANT COMMISSIONING (2051-2054)

- Handover to Operation with Authority to Operate given.
- Written Safe Systems of Work implemented.
- Asset management started.
- Commissioning plan implemented with supporting work control.
- NCR closeout and anomaly recording.
- Plant acceptance review with handover of the overall verification and validation plan.

Phase 6 – Operation (> 2054)

* Demonstration of electricity production (2055).

3.3 Preliminary Estimate of Resources

The total amount of resources used for design and R&D activities in previous representative projects is shown in Table 1.

Table 1: Summary of costs, design / R&D activities in previous representative projects

Activities		**Funds/year** (1,2)	**Mix Labs/ Industry**	**Central/Home Team (ppy)/year**
NET	1983-1998 (NET CDA)	~ 87 M€	80/20	~ 60 (till 1990) ~ 30 (by 1993) Ø ~40
EFDA	1999-2006 (ITER Technol.)	~ 100 M€	85/15	Ø ~45
JET	1973-1976 (JET design)	~ 25 M€	70/30	Ø ~40
ITER	1988-1990 (CDA) 1992-2001 (ITER-EDA) 2002-2005 (ITER-FEAT)	~ 75 M€ ~ 170 M€ ~ 25 M€	-	40-60 (Garching)+90 per HT ~ 150ppy ~ 150ppy

(1) Total cost including manpower and central team; (2) Costs inflation adjusted to 2012

The resources foreseen for the DEMO pre-conceptual design (up to 2020) and the conceptual design phase (2020-2027) are shown in Table 2.

Table 2: Annual resources summary up to completion of concept design

YEAR	**2014-2018**			**2019-2020**			**2021-2027**		
PROJECT	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
WPPMI	27	5	0	35	10	0	45	10	0
WPMAG	7.1	0.2	413	8	1	500	10	2	800
WPBB	53	4	4194	53	5	4000	50	8	4000
WPDIV	10.6	0.3	663	10	1	700	11	1	700
WPHCD	17.3	0.3	471	18	1	500	19	1	700
WPTFV	5.7	0.3	276	7	1	300	10	3	650
WPBOP	2.3	1.3	170	4	2	300	5	3	400
WPDC	4.4	0.2	0	7	0.5	0	12	1	300
WPRM	21.7	2.2	625	26	3	700	26	3	3900*
WPSAE	12.4	1.6	279	13	2.5	200	13	2.5	200
Total **K€/a**	16150	2310	7091	18100	4050	7200	20100	5175	11650
Total **K€/a**	**25551**			**29350**			**36925**		

Excluding WPMAT and WPENS
(1) lab ppy;
(2) ind. ppy;
(3) hardware (k€)
* Investment in WPRM foreseen for a Test Facility to confirm RM strategy through test-rig and trial demonstrations during the concept design phase

Since the initial publication of the European Fusion Roadmap considerable progress has been made in the understanding of the DEMO challenge. Previous estimates for the required resource to reach a conceptual design are now judged to be optimistic, and have been reviewed based on the following considerations and developments made in the pre-conceptual activities conducted to date:

- Establishing and prioritising the stakeholder requirements has given rise to an opportunity to explore a wider design space encouraging when possible innovation and development against a set of agreed concept evaluation criteria. .
    - Reduce the cost of changes later if we are required to shift architecture as we will already have characterised others that may be relevant
    - Reduce the risks of the design in general at an early stage results in savings
    - Analysing a range of diverse candidate plant architectures and evaluating them for weakness against threshold criteria will help to establish clearer development objectives.
- Discoveries in the ongoing science programme have highlighted large uncertainties in the DEMO operating point. This has stimulated the need to increase confidence in key areas using a combination of theory and experimental activities to steer the formulation of physics scenarios towards a credible point in the design space In particular, the integration of the divertor, core, and pedestal physics - combined with the plasma control and first wall protection strategy - demand special consideration to resolve the conflicts and plot a qualification route to support the design decisions in a timely manner.
- A core R&D plan must be developed, irrespective of plant architecture, to address some of the outstanding uncertainties. These uncertainties and the work required to reduce them lengthen the design decision timeline, compared with previous estimates.
- The focused design development and evaluation of the baseline has revealed the specific nature of design challenges and integration conflicts that were previously unknown. This has shown that the extrapolation of technologies from ITER to DEMO is larger than was originally assumed from JET to ITER. Specifically:
    - The technology required to meet tritium self-sufficiency is fully untested and will only partially be de-risked by the ITER test blanket modules.
    - ITER exhaust solution might not extrapolate to DEMO.
    - Development of experimental (JET/ITER) scale tritium processing and management to DEMO scale requires fundamental revision of the technology and processes to demonstrate an economically viable tritium plant.
    - Availability required is much higher than for other tokamaks. This in particular places incredible demands on the development of remote maintenance for DEMO, which must be highly sophisticated, efficient, and reliable to demonstrate FFP viability.
    - Full remote maintenance scale and complexity of much is fusion specific and fully untested
- There is significant effort required to develop and implement the appropriate technical management tools, processes and culture to assure efficient delivery of the programme of technical work. Substantial investment and effort is required at an early stage in to develop and become familiar with these approaches (that are not common practice in R&D), to lay the foundations for a robust delivery strategy. The benefits of such approaches and tools will not be fully realised until later on in the programme.
- Increased involvement of industry in the design and monitoring process from the early stage to ensure that early attention is given to industrial feasibility, costs, nuclear safety and licensing aspects.
- Increased use of resources to fulfil our international collaboration obligations (especially with China and Japan) to assist design and R&D of representative devices.

4 EVALUATION OF DESIGN OPTIONS

4.1 Systems Engineering in the selection of plant architectures

The management of the DEMO programme is complex and multi-faceted, and its technical challenges significant. DEMO must be designed and operated within a strong nuclear regulatory framework that will demand high standards in traceability of requirements and of verification and validation that the requirements have been met by the systems implemented.

Fission reactors that have benefitted from a design exploration approach founded on incremental progression, whereby a single design parameter was isolated and studied in detail typically with small-scale experimental validation. In contrast, fusion reactor design suffers from the intrinsic complexity of the tokamak (numerous interdependent system parameters) and from the dependence of plasma physics on scale – requiring large-scale experiments to validate predictions. DEMO must attempt to integrate multiple low-maturity technologies and resolve physics uncertainties in a single integrated step.

There will be multiple goals encompassing a range of stakeholder objectives that DEMO must address including; technical performance and feasibility, safety and environmental aspects, economic efficacy, and plant availability. However, for progress to be made, inroads into the following are a priority: safety, tritium breeding, power exhaust, remote maintenance, component lifetime, and plant availability. These important design drivers cannot be compromised and must be taken properly into account at the beginning of the design process [14]. One of the inherent difficulties with the design process is dealing with uncertainty. As the major step between ITER and the commercial exploitation of nuclear fusion energy, DEMO will have to address many challenges – the natures of which are – in part – still not fully known [15]. The areas with largest uncertainties with a large impact on the design layout and integration that require urgent attention have been identified [16]. As the conceptual design study of DEMO progresses, we must seek to reduce the level of uncertainty and narrow the design space.

To respond to above the DEMO programme requires a Systems Engineering design exploration and optimisation approach to explore the reactor design space and assess trade-offs and alternative concepts to arrive at a design concept that most optimally satisfies this broad range of goals and constraints [17]. For example, Section 7.5 proposes several plant concepts that have been suggested as alternatives to the baseline that may address some key risks or offer some enhanced characteristics. The purpose of the evaluation framework is to assess these alternatives, and ensure that the selected design solution has the most favourable overall characteristics in relation to stakeholder requirements, and greatest chance of successful delivery to for a given risk acceptance.
The pre-conceptual design is the initialising phase of the design process, where there must be intense focus on deriving suitable high level requirements and crystallising objectives, since decisions made during this phase will have the highest impact on the quality of the technical solutions and their ability to satisfy the broader programme goals and licencing requirements. It is therefore necessary to identify where there are competing goals, and prioritise their relative importance. This clear identification and prioritisation of goals and objectives, will inform the development of requirements, and also form the basis of the selection criteria via which alternative candidate design solutions can be evaluated to ensure an optimal design concept is pursued.

In order to facilitate this approach, candidates plant concepts that exist during the pre-conceptual design must be defined to at least an aggregated level of detail to enable comparisons against alternative designs, and the assessment against the feasibility of meeting requirements to be made. These plant concepts should be defined in consistent terms, by Systems Engineering artefacts that crystallise their anticipated performance, functional logic and concept of physical implementation, and crucially the physics and technological assumptions on which the rationale and feasibility of the design is based. With this consistent approach to concept definition, the underlying technical and physics assumptions can be scrutinised to highlight R&D gaps or feasibility issues, and screen concepts that present a high risk development path. In this way, a more holistic and traceable assessment of plant concepts against stakeholder goals and objectives can be obtained at an early stage in the design life-cycle. A possible implementation of this evaluation framework is elaborated in more detail in Annex 7.4.

As the conceptual design stage of the EU DEMO design process, plant concept evaluation assessments will continue to take place as more information relating to DEMO concepts are generated, and it may take some step-wise developments in order to reach an attractive point in the design space. Additionally, it will become necessary to perform more specific systems level design option evaluations or configuration assessments within the DEMO baseline design. Having an understanding of the interactions and interdependencies between systems is critical to inform system level concept selections. The Systems Engineering artefacts that represent the system will therefore be continually evolved and updated as the design progresses.

4.2 Concept evaluation framework

Section 4.1 introduced the concept of an evaluation framework to provide robust, auditable assessments of candidate plant and system options, and outlined the pivotal role of the framework in the pre-conceptual and conceptual design activities. This section introduces some of the requirements of the framework and the possible approaches to implement it. It is not however the intention to fully define the framework and its implementation in this document. The mechanics of the framework, and the attributes to be assessed will be developed as early as possible in consultation with industry, and the attributes to be assessed by the framework be agreed in consultation with stakeholders.

For complex, multi-tiered problems, a hierarchical framework of Figures of Merit (FoMs) can be created to map high level characteristics of interest to stakeholders to system attributes at lower level. Each FoM is evaluated through its scoring function, and the resulting scores are combined or 'rolled up' at each level of hierarchy to achieve an overall numerical score of the concepts option under study. This allows scoring and assessment of FoM to take place at domain level to ensure traceability and robustness of the assessment, whilst still allowing comparison of concepts at high (plant) level.

A key aspect of the methodology is that alternative concepts shall not be assessed purely on the potential technical performance that each concept offers, but that all attributes that are of importance to stakeholders in the realisation of fusion are taken into account. This includes the consideration of various key thematic areas, such as: safety & environmental issues, plant performance, cost, schedule, and technical risk.

A preliminary set of thematic areas for the evaluation of DEMO concepts is shown in Annex 7.4, along with associated subsets of high level figures of merit (FoM – L1). These high level FoMs are broken down into lower level FoMs (L2) and deeper down to the system levels in a hierarchical structure, all of which will eventually relate to one or more high level FoMs. The proposed list is not exhaustive and is intended as an indication of the direction to be followed. The definition of a full set of FoMs and the associated hierarchical structure will be the result of discussions with stakeholders and domain experts.

The methodology is not aimed at automatically calculating the best concept options, but it will elicit judgements and biases and exposes them to objective scrutiny. It also provides an audit trail for the chosen design options against which the effects of technological and programme developments can be compared.

A number of DEMO candidate architectures to be evaluated shall be proposed. They will be defined to identify explore more robust and reactor-relevant solutions to address areas of particularly high feasibility concern or improve the safety and licensing prospects for the design. The design combinations described in Annex 7.5 are preliminary examples in this direction.

5 CONCLUSIONS

The purpose of this document is to describe the basis for a revised DEMO design and R&D plan by outlining a strategy on how to deal with the uncertainties in the physics and technology basis. We aim to identify the building blocks upon which more detailed development approaches will be based in the future in order to focus activities during the early stages of implementation. This strategy has been developed as part of the update of the EU Roadmap to Fusion Electricity: (i) to integrate the programmatic implications and minimize the impact arising from the foreseen delay of ITER construction on the demonstration of electricity production; and (ii) to strengthen the exploration of the available design space in view of accelerating the process to identify the most attractive design solutions. More emphasis will be put on determining the location of DEMO in between ITER and a commercial FPP, based on the existing gaps and the development risks that are deemed acceptable. However, this task shall to be carried out with the involvement of industry in order to ensure that feasibility issues and regulatory challenges expected to be addressed for obtaining the license to construct and operate a nuclear fusion plant are not overlooked, and to ensure that the assessment of maturity and technical readiness levels of the proposed technologies and uncertainties of the physics assumptions, are substantiated with an estimate of the development risks, development costs and development times.

The key phases of this new schedule to arrive as early as possible to a robust DEMO concept design are described, together with the main aspects of a proposed systems engineering approach to explore a broader design space. In the pre-conceptual design phase, multiple DEMO architectures will be investigated in parallel and compared against each other. An optioneering approach is introduced and described, along with some of the design options to be studied in the early stages of implementation. This is proposed to enable decision-making against a range of relevant figures of merit. The overall approach shall be discussed with stakeholders.

The delay in the ITER schedule need not overly affect the DEMO design schedule, or jeopardise the demonstration of fusion electricity by the 2050s. The DEMO conceptual design phase is anticipated to reach completion in the late 2020s, in time for the feedback of ITER D-T operational to take place, and for the engineering design and construction activities to occur early enough to still deliver electricity to the grid in the 2050s. The resources required for the pre-conceptual and conceptual design phases have been estimated.

6 ACKNOWLEDGEMENTS

In particular, the contributions of Matti Coleman, John Anthony, Richard Brown, Hartmut Zohm, and Robert Ellis are acknowledged, together with the valuable support provided by the PPPT Expert Group.

7 ANNEXES

7.1 Lessons learned from GEN-IV

We are very grateful to the ASTRID and MYRRHA teams for the advices and observations reported below that they have made.

- Fission projects follow a pattern of evolution in each successive plant design, with careful progression in key areas backed up by some operational data. ASTRID has drawn from Superphenix and the Phenix machine before that. MYRRHA has matured from extensive test bed development and operation of the MEGAPIE experiments.
- The plant design should drive R&D and not the other way round, but the design should be kept flexible enough to incorporate possible R&D breakthroughs in areas where they would have a large impact.
- It is important to consider from the beginning that fusion as a nuclear technology will be assessed with full nuclear scrutiny by the regulator. To this end, early engagement with a licensing consultant is needed to understand and tackle potential safety implications through design amelioration.
- There is a need for a traceable design process with a rigorous Systems Engineering approach. Design choices should be made within a traceable context of functions and requirements so that future lurches from one decision path to another are not made without full understanding of the requirements originally assigned and the potential implications.
- The production of electricity should be the main objective of a fusion development program.
- The technical solution should be based on maintaining proven design features (e.g., using mostly near-ITER technology where possible) to minimize technological risks, but both highlighted the need to take risks when the reward is significant and there is a back-up plan.
- Reliability and maintainability should be key drivers: allow for design margin (over-design) where technology limits and budget will allow, since this will increase machine longevity, reliability and capability, when considering enhancements.

7.2 Physics Stepladder Approach

One of the recommendations of the EU DEMO stakeholder group is that DEMO should retain attractive technical features to allow a conceivable extrapolation step to a first-of-a kind commercial power plant. It is however not obvious how to derive from this a DEMO design point. In fact, the present EU approach examines a variety of options which, depending on the assumption of available physics and technology basis at the time of DEMO construction, range from a conservative pulsed device largely based on the ITER Q=10 scenario ('DEMO1') to a steady-state machine with more aggressive physics and technology assumptions ('DEMO2').

For a credible extrapolation, the plasma scenario must not foresee a large development step from DEMO to the FPP, since there is no machine other than DEMO itself to qualify it (even if 'satellite' devices exist, the credibility of improvements made in these will not be high enough to be incorporated into a commercial FPP unless they have been demonstrated in the DEMO environment). In a similar manner, ITER should prepare the DEMO scenario since it will be the largest device of its kind and the one that allows studying α-particle dynamics and self-heating under conditions closest to DEMO. While satellite devices such as JT-60SA will play an important role in developing plasma scenarios, a scenario developed there would always be tested in ITER before applied to DEMO.

We hence propose a stepladder approach ITER-DEMO-FPP that keeps the plasma scenarios as close as possible such that DEMO effectively becomes a technology demonstrator and not a plasma physics experiment. While a credible plasma scenario development requires a careful time-dependent plasma transport analysis considering kinetic and current profiles, we use here as a first step a 0-d approach that keeps important dimensionless plasma parameters similar and essentially varies machine size and with it the fusion power and electricity output. We chose to describe the plasma scenario in terms of dimensionless quantities β_N, q, H and f_{GW}. In addition, we chose a constant absolute value of the density since this is a key parameter for the divertor performance. We note that this implies that the dimensionless parameters ρ^* and ν^* will not be constant, and a careful anaylsis is needed to determine what the impact of this choice will be in terms of extrapolability.

This leaves open the choice of machine parameters such as aspect ratio (A), major radius (R), and magnetic field (B). For illustration, we assume that A is kept constant at the ITER value. We also fix the plasma shape (e.g., elongation and triangularity) to the values used for ITER, but this can also be changed. As an example, an increase in elongation will be very favourable for the bootstrap fraction since it allows running higher q at the same current.

The assumption of constant f_{GW} and absolute density gives a prescription how to vary B and R from machine to machine. This leads to

$$n \propto f_{GW} \frac{B}{Rq} \tag{1}$$

which, because of the assumption of constant *q*, leads to *B/R* = const. Then, at constant q, β_N and A in this constraint leads to a scaling of

$$P_{fus} \propto R^7 \propto B^7 \tag{2}$$

which means that both B and R will increase according to $P_{fus}^{1/7}$ in the stepladder.

We note that increasing both B and R will also strongly increase Q, so that ignition in itself will not be a problem in this approach. We further note that the power needed to drive the current in steady state varies surprisingly weakly through the stepladder since for RF systems, one can derive

$$P_{CD} \propto \frac{B}{q^2} \frac{f_{GW}^2}{\beta_N A} (5 + Z_{eff})(1 - const. \sqrt{A} q \beta_N) \tag{3}$$

which in our approach only depends linearly on B in the regime where Z_{eff} is significantly smaller than 5. It follows that P_{CD} increases only with $P_{fus}^{1/7}$, so that going from DEMO to an FPP will lead to a significant decrease in recirculating power fraction, but since we do not change the physics scenarios and its assumptions, this should be a highly credible step.

Concerning the exhaust problem, we will assume here that DEMO and an FPP use the ITER divertor solution. As figure of merit for divertor performance, we use the power flowing into a ring of surface $2\pi R\lambda_q$, where λ_q is the power decay length in the outside midplane, scaling mainly with poloidal gyroradius, i.e. $\lambda_q \propto q/B$ if we neglect the temperature variation (due to the strong temperature dependence of power flux conducted in the SOL, the separatrix temperature is not expected to vary strongly within the stepladder. Our exhaust criterion hence becomes

$$\frac{P_{sep}B}{qR} < \left(\frac{P_{sep}B}{qR}\right)_{ITER} \tag{4}$$

where P_{sep} is the power crossing the separatrix after subtracting the radiation and the index ITER refers to the Q=10 scenario at full current and field. Since in our approach, B/(qR) is kept constant, it follows that the allowable P_{sep} is constant, too. On the other hand, in order to stay in H-mode, P_{sep} must exceed the power threshold P_{LH} by a fraction f_{LH}, so that there will be a window for P_{sep} that must be finite for any machine design in our stepladder. This window for P_{sep} decreases with machine size and the core radiation fraction will have to be increased in order to fulfill condition (4).

This approach can be used to get a first impression of parameters in the stepladder approach. For illustration, we assume an FPP with P_{fus} = 3.5 GW and 60 % bootstrap fraction at B=6.1 T and R=8.5 m, resulting in $P_{CD} \approx$ 120 MW, close to the PPCS model C [18], the net electrical output is of the order of 1 GW, and the recirculating power fraction is about 20 %. We can now analyse where a DEMO should sit on the stepladder. Assuming we want to generate several 100 MW as proposed by the Stakeholders [5], we can aim for P_{fus} = 2 GW which would give close to 0.5 MW net electric power at a recirculating power fraction of 35 %, which would be unacceptable for an economic FPP, but as outlined in the previous section the credibility of achieving the 20% mentioned above for the FPP would be quite high. This means that B and R should be lower by $(3.5/2)^{1/7}$ = 1.083, so that DEMO sits at 7.85 m and 5.6 T. Finally, we can also determine how ITER should be operated to demonstrate this scenario. Scaling down the radius by 7.85/6.2 = 1.26, the fusion power will be around 400 MW, and should be operated at I_p = 9 MA, B = 4.5 T.

This numerical example is of course by no means optimized, but indicative of the feasibility of the approach. More work is needed to optimize the step size and FPP operational parameters, and this should be an active area of work within PPP&T in the coming years. A very interesting step will be to also examine how the DEMO performance varies as function of plasma parameters, so that DEMO could be conceived as a machine that has two phases, corresponding to DEMO1 and DEMO2, but within one design.

Finally, while the present approach targets the plasma scenario, a similar exercise should be conducted concerning technology developments and the integration of physics/technology constraints, again with the aim to demonstrate the necessary technology in DEMO such that the step to the FPP becomes credible. For example, one might conceive building DEMO for a higher maximum B-field than needed in the similarity scenario if this is deemed necessary for demonstrating the magnet technology (such a step would also increase the flexibility of the device for adjusting the scenario).

7.3 Foreseen deliverables of the conceptual design phase

Table 3 below provides examples of related deliverables for the conceptual design:

Table 3: Deliverables for the Conceptual Design Review

Plant Requirements Document Overall Mission and Requirements Measures of Effectiveness[6] Verification and validation (qualification) plan.
Operational Concept Description Including Physics basis guidelines and operational scenario
System Requirements Documents (SRD) SRD for each major plant system Identification of Interfaces between systems
Trade-Off studies particularly for sensitive mission requirements versus engineering realism and manufacturing feasibility to satisfy the corresponding performance requirements
System Architectural Definition, Structure, Systems and Component classifications. System Structure: Functional Breakdown Structure (FBS) Plant Breakdown Structure (PBS) System Behaviour: Functional Flow Analysis, Functional Flow Block Diagrams (FFBD) States & Modes Diagrams Process Flow Diagrams (PFD) Piping & instrumentation Diagram (P&ID)
System Budgets Life cycle cost analysis Power Consumption Budget Materials; Fuel; Waste Inventory
System Design Description Documents Report describing the concept design rationale for each system inc. material specifications. Compliancy measures with requirements. Design Reviews (Gates) at plant, system, and component levels.
System Integration 3D CAD model of Plant
Preliminary Safety Report
Plant RAMI Report Preliminary Failure Modes, Effects and Criticality Analysis Report Worst Case analysis Maintainability / Inspection Analysis
R&D and technology development plan required to complete the design effort and support licensing of the reactor
Preliminary Manufacturing / Producability Plans
Preliminary Assembly & Maintenance Plan
Preliminary Test & Commissioning Plan
Preliminary Decommissioning & Disposal Plan
Programme Management Plan (for EDA phase) R&D Plan Manpower / Skills requirements Programme Risk Analysis

6 Measure designed to correspond to accomplishment of mission objectives and achievement of desired results. They quantify the results to be obtained by a system and may be expressed as probabilities that the system will perform as required.

7.4 A tentative list of thematic areas and figures of merit for application in the evaluation framework

This is a preliminary list and will evolve as examples from industry (and in particular Gen-IV) are taken into consideration.

Table 4: Preliminary thematic areas and FoMs, including indications of a hierarchical structure

Thematic areas	**FoM - L1**	**FoM - L2**
Safety, Environment and Sustainability	Radiological risk to the public	Need for off-site emergency response (y/n) Normal operation tritium release Accident scenario tritium release …
	Inherent safety risk	Consequence of category 5 accidents Consequence of category 4 accidents …
	Radiological waste	Quantity of Intermediate Level Waste Quantity of Low Level Waste Radiotoxicity at 100 years after discharge …
	Radiological risk to workers	No evacuation required (y/n) Collective dose rates …
Plant Performance	Operational lifetime	Non-replaceable component life-times …
	Operational availability	Planned maintenance operation durations In-vessel component life-times Inherent system availabilities …
	Tritium self-sufficiency	Tritium breeding ratio Tritium start-up inventory …
	Capacity factor	Net electricity production Pulse duration Dwell duration …
	Robustness of plant operating point	System performance margins Sensitivity to physics assumptions …
Cost	Plant capital cost	System material costs System manufacturing costs …
	Operational costs	Component replacement costs …
	Development cost	System TRL assessments …
	Cost uncertainty	System TRL assessments …
Schedule	Development time	System TRL assessments Supporting facilities …
	Schedule uncertainty	System TRL assessments Programme dependencies …
Technical Risk	Integrated technical risk assessment	System technical risk assessments …

7.5 Examples of design options for early investigation

The task of choosing an appropriate set of design parameters and engineering technologies for a DEMO fusion reactor involves trade-offs between the attractiveness and technical risk associated with the various design options. In particular, more robust and reactor-relevant solutions are required to address the problems of the power exhaust and the first wall protection, which have been identified to be some of the most critical interfaces during the work conducted to date in the PPPT. Also, safety is expected to play an important role in the ultimate selection of plant design features and operating conditions (e.g., choice of materials, coolants, etc), and important safety analyses (e.g., in-vessel and ex-vessel loss of coolant accident) must be carried out early to guide the evolution of the DEMO design. In particular, coolant circulation and power conversion systems must be both highly safe and reliable, as they communicate between the plasma and the balance of the plant, transporting energy, and possibly tritium and radioactive impurities that must be strictly controlled. Finally, the benefits and risks of design solutions that rely on more aggressive physics and technology assumptions must be studied to determine their attractiveness, together with a clear identification of inherent feasibility issues and the resulting R&D requirements. This task is expected to be carried out with the involvement of industry in order to ensure that feasibility issues and regulatory challenges expected to be addressed for obtaining the license to construct and operate a nuclear fusion plant are not overlooked, and to ensure that the assessment of maturity and technical readiness levels of the proposed technologies and uncertainties of the physics assumptions, are substantiated with an estimate of the development risks, costs and times.

Various design concepts shall be investigated for a DEMO plant that differs substantially from the point of view of readiness of the technical assumptions being made in plasma physics and technology (see below). This should be based on the progress made to date with the studies done on the so-called DEMO2 and should include a plant with: (i) optimistic physics assumption, optimistic (but realistic) technology assumptions; and (ii) optimistic physics assumption, and very advanced technology assumptions. Design reviews, criteria have to be developed and implemented that need to be harmonized with the Systems engineering processes under development.

Based on the considerations above the following examples of designs are proposed for investigation:

a. DEMO1-SN [baseline]

The DEMO1 single null (SN) configuration is based heavily on the ITER design and is currently the baseline architecture; that is to say it is currently considered to have the highest chance of meeting all of the DEMO high level requirements. A baseline design is used as a reference and is used for more detailed design integration work to understand and resolve interface issues, and to keep part of the work in the distributed projects focussed. Many solutions generated for the baseline are applicable or transferable to other architectures. Studies are planned to address plant layout implication resulting from sizing of safety and/or power conversion systems associated with various coolant choices considered. This should include for instance (i) the analysis of the overpressure resulting from a loss of coolant accident (LOCA); (ii) the feasibility and safety issues of an energy storage system (ESS), etc.

b. DEMO1 with Double Null (DN) divertor configuration

The constraints coming from specific DEMO requirements (e.g., to select cooling systems and coolant operating conditions for self-sufficient tritium breeding and efficient power conversion and electricity production) bear a strong impact in the design and technology selection process of the components surrounding the plasma. In particular, the choice of the divertor configuration and first wall design are crucial design and operation aspects, and there are still uncertainties as to whether some of the design choices and technical solutions adopted by ITER can be used or alternative solutions are required. A double null (DN) divertor configuration is viewed to be attractive. It could be possible to distribute the divertor load relatively equally on the two outer targets and to increase the level of SOL/divertor radiation. In addition the problem of charged particle loads on the top of the machine, which is extremely challenging for LSN, is resolved by turning this region into a second divertor. The strongly reduced radial transport on the inboard side might allow operation without high heat flux components and low clearance in this area. A DN DEMO design would also largely avoid the radial-vertical coupling in case of current density profile perturbation, leading to mainly radial plasma perturbations and less plasma surface interaction at the top. However, while for LSN designs (e.g. ITER) the achievable performance, measured as the maximum plasma elongation that can be controlled, has been improved in recent decades by a careful optimization of the positioning of plasma and toroidally conducting structures, improved DN design options need to be developed. Also for this design option various integration aspects of a physical (e.g. P_{LH}) and technical (e.g. TBR reduction) nature need to be analysed in detail.

c. DEMO1 with an extended pulse (e.g., > 4 hrs)

For the same relatively conservative physics and technology assumptions as in the DEMO1 baseline, the design implications of extending the pulse length by a factor of 2 to 4 in an inductive DEMO design will be investigated, including: central solenoid and tokamak design issues, and the effect on the BoP. An understanding shall also be sought from the SHG on the relative attractiveness of longer pulse machines.

d. “A flexi-DEMO”:

A machine designed to initially operate in a short pulse mode (e.g., 1 hr), with conservative physics assumptions, but that could move to steady-state operation with an improvement in physics and current drive. The scope and extent of feasible engineering upgrades and improvements in physics shall be assessed, in order to gain an understanding of what range of operating scenarios could be covered within a single machine.

e. DEMO2- (steady state operation) Optimistic physics assumption, optimistic (but realistic) technology assumptions

A steady-state machine with more optimistic physics assumptions than DEMO1-SN, but framed within the same technology constraints. This option is naturally more attractive from a performance perspective, however presents a higher level of development risk, with larger uncertainties.

f. In addition, more advanced DEMO design options with “**Optimistic physics assumption”, and “Advanced technology assumptions”** could be investigated bearing in mind the approach and the criteria described above.

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