Fusion Engineering and Design 89 (2014) 273–279

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Reducing risk and accelerating delivery of a neutron source for fusion materials research

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HIGHLIGHTS

- Proposed neutron source for fusion materials – FAFNIR – n(d,C) stripping source.
- Near term technology, reduces risk compared with IFMIF, timely data production.
- Technical, economic and programme needs assessed, compatible with EU Roadmap proposals.
- Safety case impacts regulatory role for source, now mainly stakeholder insurance.

ARTICLE INFO

Article history:
Received 12 August 2013
Received in revised form 18 January 2014
Accepted 21 January 2014
Available online 3 March 2014

Keywords:
Materials irradiation
Neutron source
Accelerator
Fusion materials
IFMIF

ABSTRACT

The materials engineering database relevant to fusion irradiation is poorly populated and it has long been recognized that a fusion spectrum neutron source will be required, the facility IFMIF being the present proposal. Re-evaluation of the regulatory approach for the EU proposed DEMO device shows that the purpose of the source can be changed from lifetime equivalent irradiation exposure to data generation at lower levels of exposure by adopting a defence in depth strategy and regular component surveillance. This reduces the specification of the source with respect to IFMIF allowing lower risk technology solutions to be considered. A description of such a source, the Facility for Fusion Neutron Irradiation Research, FAFNIR, is presented here along with project timescales and costs.

1. Introduction

The need to establish a facility capable of irradiating materials with a neutron spectrum that mimics that generated by a fusion power plant was identified in the 1980s. The historical role advocated for a fusion relevant neutron source includes population of the materials database with engineering relevant information, provision of 14 MeV neutron irradiation data to validate and calibrate alternative irradiation techniques and qualification of materials to a lifetime use equivalent of 150 dpa. The International Fusion Materials Irradiation Facility (IFMIF) [1,2] is the result of an assessment of different concepts intended to provide this. The resulting IFMIF specification requires machine availability of 70% from two accelerators operating at the highest cw power recorded, imposing 1 GW m^{-2} of beam power on a flowing lithium target. These demands are challenging and present a high technological risk. Although funded by the European and Japanese ITER members under the Broader Approach, no timetable is foreseen that will deliver materials testing data on a timescale commensurate with the start of DEMO construction proposed in the newly-adopted EU Fusion Roadmap [3].

This obviously impacts upon the design programme for power plants and has prompted this study to assess, within the context of regulatory licensing and the engineering materials perspective, the actual requirements for the neutron source to precede this Roadmap DEMO milestone. This approach shows that a facility of reduced intensity, based on (near-) available

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http://dx.doi.org/10.1016/j.fusengdes.2014.01.068

technology, can provide a valuable resource if realized on a suitable timescale.

2. Requirements of a neutron source

The role of a neutron source within the fusion programme is primarily to populate the materials database with engineering design relevant information. Within this role is the provision of 14 MeV irradiation data to validate and calibrate the more readily available fission and ion irradiation data and to strengthen predictive modelling capability. The original intention of IFMIF was the qualification of candidate materials up to a full lifetime use (assumed in [1] to be 20 years), equivalent to approximately 150 dpa [1,2]. This need is based on the perception that such qualification is necessary for regulatory licensing of a fusion power plant. A re-assessment of the regulatory requirements and those of the engineering materials indicates that some of these original specifications can be relaxed.

2.1. Requirements determined by regulatory considerations

The regulator will insist that materials used for the construction of the radiological confinement boundary are demonstrably safe over the lifetime of the plant whilst investors and stakeholders will seek reassurance of the integrity of the whole plant.

Application of "defense in depth" strategies, as adopted by ITER [4] should allow the regulatory requirements to be met without the need for a prolonged irradiation qualification campaign. By defining the primary confinement boundary to be the vacuum vessel and its extensions, the in-vessel components such as the plasma facing first wall, tritium breeder blankets and divertor are no longer part of the radiological control. This circumvents the need of end-of-life testing for the in-vessel components and the inherent difficulty in achieving high dpa material, joint and component irradiation by a 14 MeV neutron source.

This approach necessitates that the vacuum vessel material must be adequately characterized (along with materials comprising any of its extensions such as auxiliary heating systems). Simulation shows the high energy neutron flux at the vacuum vessel wall is over 10^4 lower than at the first wall and considerably softer with less than 30% of the flux having energies above 0.1 MeV. The flux below this energy is reduced by $\sim$600 compared to the first wall [5] so that over the 30 year lifetime specified for the DEMO device the exposure to the main vessel will be of the order 0.2 dpa. Qualification of materials to this exposure would not require lengthy irradiation times in even a modest flux source. Further mitigation can be provided by additional confinement structures so the requirements to be met by the neutron source become primarily the provision of data to assure investment protection and engineering design substantiation.

This will be difficult to achieve in the absence of many years irradiation by a 14 MeV neutron source. In addition, the proving of joining techniques and component assemblies will be severely limited in an accelerator driven source due to volumetric constraints. This inherent uncertainty in the material properties under irradiation draws many parallels with the 20th century realization of first-generation fission plants, particularly in the realm of design criteria and their interaction with safety and materials activities.

Given the substantial gaps in understanding materials performance within fission reactors and the absence of nuclear design codes, a pragmatic approach was taken to facilitate the design and continued operation of the plants, re-assuring the regulator and enabling the long-term development of fission design criteria. Most importantly, the safety case was formulated with key statements to ensure continued plant operations were dependent upon resistance to failure but that neither advance knowledge of end-of-life material performance nor exhaustive experiences of the failure modes were required.

Formulating the safety case in this way meant that rather than exhaustive testing and development programmes in advance of the build, ongoing demonstration of regulatory compliance was instead dependent on continuous in-service assessment to demonstrate an acceptably low probability of failure to the regulator. This was achieved by extensive surveillance schemes; withdrawal of material and joint specimens at periodic intervals allowed tracking of changes in properties and development of models to allow interpolation and extrapolation with confidence. Understanding of effects of each variable (and physical processes) over the life of the device facilitated good predictions and ultimately regulator confidence. This multi-faceted approach including safety expertise, dedicated experiments and supporting materials modelling, allowed the licensing of first-of-a-kind plant types. Substantial improvements in understanding of both material behaviour and mechanisms of failure over the life of the project were ultimately iterated into the development of new design criteria to guide the design of upgrades and future plants.

This early fission experience provides a number of important lessons for fusion:

(i) The approach to licensing cascades into the safety case and important decisions on the scope of design criteria development in advance of the plant build.
(ii) Design criteria and their development must be undertaken in close co-operation with dedicated supporting materials experiments and materials modelling activities.
(iii) Complete understanding of the environment is not needed; therefore end of life fusion neutron irradiation is not required before the design and build of DEMO. Instead only an insight into the effects is needed with margin provided for the inevitable 'unknown unknowns' that will be revealed during the lifetime of the project.
(iv) Accelerated testing programmes pursued in parallel to operations are important to facilitate long-term learning.

To minimize the scope of work required to facilitate the realization of DEMO, this pragmatic approach, adjusted for a modern context and regulatory system, offers many attractions. However, minimizing the amount of work in advance does raise technical risks for the design. In particular, designs may be susceptible to crippling 'unknown unknowns' such as new failure modes and their interactions, which could serve to reduce component lifetime and therefore plant availability.

2.2. Requirements determined by DEMO operation

The purpose of the EU DEMO device was re-assessed in 2012 [6], emerging as a technology demonstrator capable of delivering 500 MWe but with limited availability of 30%. Furthermore, it is envisaged that the plasma facing first wall ($\sim$2 MW m^{-2} neutron flux) components will be replaced after an exposure equivalent to 20 dpa in steel, a calendar time equivalent to approximately 4 years assuming a damage rate of 15 dpa per full power year (fpy) and 30% availability. This relaxes the operating characteristics of the neutron source significantly from the IFMIF requirement.

2.3. Requirements determined by materials database

A re-assessment of the neutron source requirements from an engineering materials perspective shows that some of the original requirements can be relaxed. For example, materials degradation phenomena such as irradiation creep, volumetric swelling, and phase instabilities approach saturation at damage levels above