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Fusion materials science and technology research opportunities now and during the ITER era

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ABSTRACT

Several high-priority near-term potential research activities to address fusion nuclear science challenges are summarized. General recommendations include: (1) Research should be preferentially focused on the most technologically advanced options (i.e., options that have been developed at least through the single-effects concept exploration stage, technology readiness levels >3), (2) Significant near-term progress can be achieved by modifying existing facilities and/or moderate investment in new medium-scale facilities, and (3) Computational modeling for fusion nuclear sciences is generally not yet sufficiently robust to enable truly predictive results to be obtained, but large reductions in risk, cost and schedule can be achieved by careful integration of experiment and modeling.

1. Introduction

The foundational goal of the worldwide fusion energy research programs is to provide the science and engineering basis to recreate and control the power of the sun on earth. With the dramatic improvements in scientific understanding of heating and confining dense plasmas over the past several decades (to be culminated in studies to be performed in ITER and complementary large scale international plasma machines), increasing attention is being placed on resolution of a series of high-level materials and fusion nuclear science feasibility issues that stand in the way of development of practical fusion energy. A panel of researchers was recently convened to respond to a request from the Office of Science, U.S. Department of Energy to evaluate compelling fusion materials science and technology research opportunities for the next 10 years, with a particular focus on research needed to fill knowledge gaps in order to create the basis for a Demonstration (DEMO) fusion reactor [1]. The assessment utilized recent evaluations on fusion energy research opportunities [2–4] and also solicited additional research community input. Key findings and recommendations from this evaluation are summarized in the following.

As noted in Section 2, the scientific challenges associated with fusion materials and nuclear technologies are extraordinary. There are several pronounced differences in operational environments from current fusion devices and that of ITER and subsequent fusion energy systems. For example, the plasma facing components

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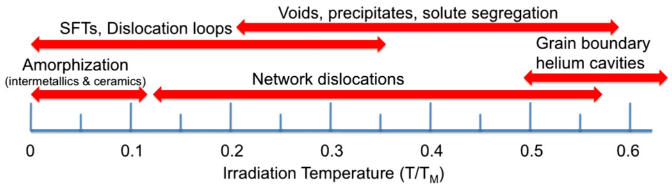


Fig. 1. Overview of temperature dependence of defect microstructures produced in irradiated materials.

(PFCs) in the divertor region of ITER will be subjected to ion fluences that are ~5000 times greater and neutron fluences that are about one million times greater than typical current large-scale plasma machines such as JET. The corresponding environment for PFCs in a DEMO may be an additional 5 and 100 times greater ion and neutron fluence, respectively, compared to ITER. Another important consideration is that the materials comprising the components for the PFCs, structure, and blanket regions of DEMO reactors will operate at significantly higher temperature compared to current plasma devices. This can lead to a host of different emergent phenomena. For example, time-dependent plastic deformation (thermal creep) is typically negligible for operating temperatures below 0.4 T_M (where T_M is the absolute melting temperature) and can become very pronounced at higher operating temperatures. Similarly, the microstructural and property evolution of materials exposed to neutron irradiation is strongly dependent on temperature. Fig. 1 summarizes some of the main microstructural regimes for irradiated materials. Completely different microstructural features (with accompanying different effects on properties) are produced in different operating temperature regimes [5]. Analogous temperature-dependent behavior occurs for a variety of plasma-materials interaction (PMI) phenomena. For example, depending on the exposure temperature several different surface features including surface pits, blistering/exfoliation and nano-tendril formation can be predominant in PFCs exposed to intense plasmas [6,7]. Therefore, experience obtained in ITER at relatively low operating temperatures for many components may not be applicable for follow-on fusion energy systems that would operate at higher temperatures.

2. Key scientific challenges for fusion materials and technology

Three overarching grand challenges were evaluated that comprise fusion nuclear science: taming the plasma-materials interface, conquering nuclear degradation of materials and structures, and harnessing fusion power (tritium science, chamber technology and power extraction).

2.1. Plasma materials interactions

For plasma-facing materials, the well-known overarching challenge is associated with accommodation of extreme heat and particle fluxes along with intense fusion neutron damage. The material surfaces directly facing the plasma are exposed to continual energetic bombardment of plasma particles that both exhaust heat and "recycle" the hydrogen fuel. The boundary plasma continually rearranges plasma-facing materials through sputtering, plasma transport and redeposition; for example a surface atom in DEMO may be removed and redeposited over a billion times in a single year. Of particular importance is that localized erosion fluctuations must be considered, not just the global average erosion. In addition, potential entrapment of tritium from the fusion plasma by redeposited layers is an important safety issue. Simultaneously the surfaces impose strict boundary conditions for the fusion plasma, making for a highly non-linear, evolving coupled physical system.

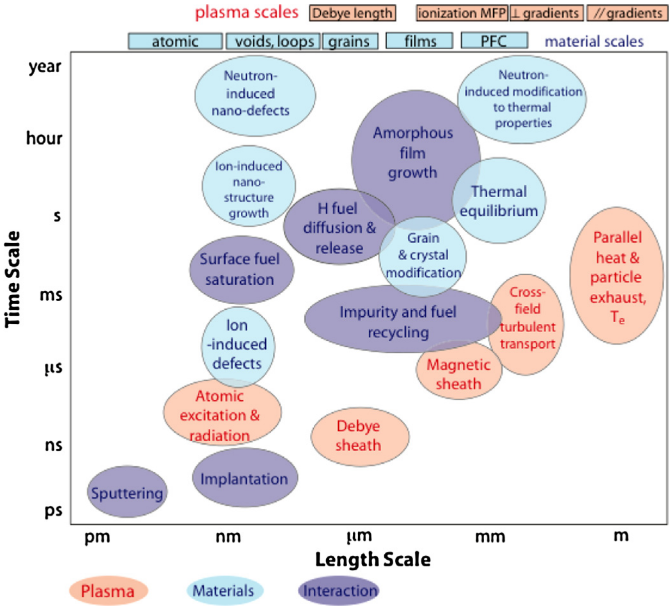


Fig. 2. Overview of the coupled multi-scale phenomenon associated with plasma-materials interactions.

The plasma-materials interactions include physical phenomena that occur over a vast range of length and time scales, as depicted in Fig. 2. Different multiscale phenomena are of importance when considering PMI issues from the perspective of condensed matter, near-edge plasma, or coupled plasma-materials interactions. Fusion neutrons produce volumetric defects and transmutation products, particularly helium and hydrogen. The plasma presents strongly perturbing physical processes at material surfaces, through erosion and re-deposition, and hydrogen and helium implantation. While these effects are largely separable due to the different scales, the intense heat flux and high material operating temperatures, and associated thermal gradients couple these multi-scale effects. Thermal loading can have steady, transient, and off-normal features that aggravate degradation mechanisms and can lead to failure. It is necessary to understand and predict failure modes of surfaces, bulk material, and material interfaces in this environment due to thermal and mechanical fatigue and transient electromagnetic loading, combined with radiation damage effects. This knowledge is required to establish potential plasma and materials operating conditions that will lead to acceptable PFC lifetimes in this extreme environment.

2.2. High performance fusion radiation-resistant materials

For material structures, the overarching challenge is to maintain mechanical and structural integrity by designing highly efficient radiation self-healing nanostructures that are resistant to unprecedented levels of displacement damage and nuclear transmutation products. Atomic displacement damage in a DEMO reactor corresponds to ejecting every atom from its lattice site more than 50–150 times. This lattice damage interacts with reactive and insoluble gases (e.g., H and He) produced by high-energy nuclear reactions to alter the microstructural evolution. Consequently material properties gradually degrade with time through mechanisms such as low-temperature hardening and embrittlement, phase instabilities, solute segregation, precipitation, irradiation creep, volumetric swelling, and high-temperature helium embrittlement [8]. These damage mechanisms are poorly understood

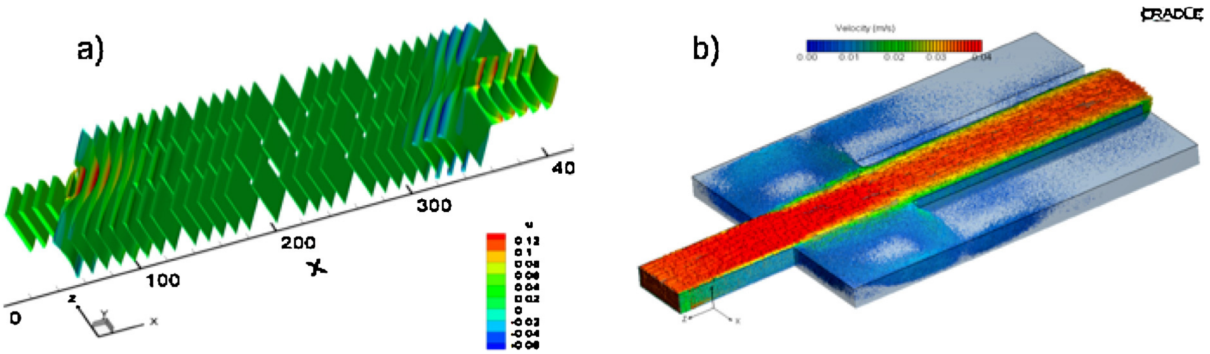


Fig. 3. 3D MHD simulation of flow velocity distribution to 3 blanket channels from a common manifold. (a) By appropriate selection of channel dimensions, uniform flow can be achieved. (b) In the absence of a magnetic field, the flow is restricted to a central channel.

because radiation damage is inherently a hierarchical, multi-scale phenomenon involving atomic- and meso-scale physical processes that span more than 20 orders of magnitude in time scale and >8 orders of magnitude in length scale.

The potential impact of helium-induced degradation of reduced activation ferritic/martensitic steels over their entire operating temperature range illustrates the magnitude of the scientific challenge. Due to its low solubility, helium precipitates into gas bubbles. At low irradiation temperatures, the helium synergistically interacts with damage-induced hardening resulting in severe degradation of fracture toughness and potentially causing intergranular fracture when the grain boundary fracture stress drops below the cleavage fracture stress [9–11]. At intermediate irradiation temperatures helium bubbles may cause unstable void growth, possibly leading to unacceptable volumetric swelling and enhanced creep. At high irradiation temperatures, helium bubbles at grain boundaries can grow and coalesce under stress, resulting in severe degradation of creep and fatigue properties. This 14 MeV neutron-induced material degradation underscores the critical need for an intense fusion relevant neutron source enabling investigation of the effects of irradiation on bulk material mechanical and physical properties.

Existing engineering design codes such as the ASME Boiler and Pressure Vessel Code have been used for decades to design reliable, safe, economical fission reactors. However, these existing codes have limitations that will hinder the design and fabrication of high performance fusion components unless significant advances are made. For example, for flow localization and ratcheting, the current design rules are oversimplistic to permit conservative design without sophisticated analysis [12,13]. In other cases such as creep rupture, empirical rules are used due to a lack of scientific understanding [14,15]. Therefore, there is no guarantee these rules are conservative, especially if the operating conditions are far from the conditions under which the empirical rules were developed. Hence, a move toward science-based design rules is needed [16,17]. An engineering design consideration that has not yet received sufficient attention due to the relative immature state of DEMO engineering designs is possible high-frequency, low-amplitude cyclic fatigue stress due to periodic variations in the plasma and/or flowing coolant. For comparison, creep-fatigue issues are of enormous importance in inherently steady-state Na-cooled fast-spectrum fission reactors due to minor perturbations in the coolant flow.

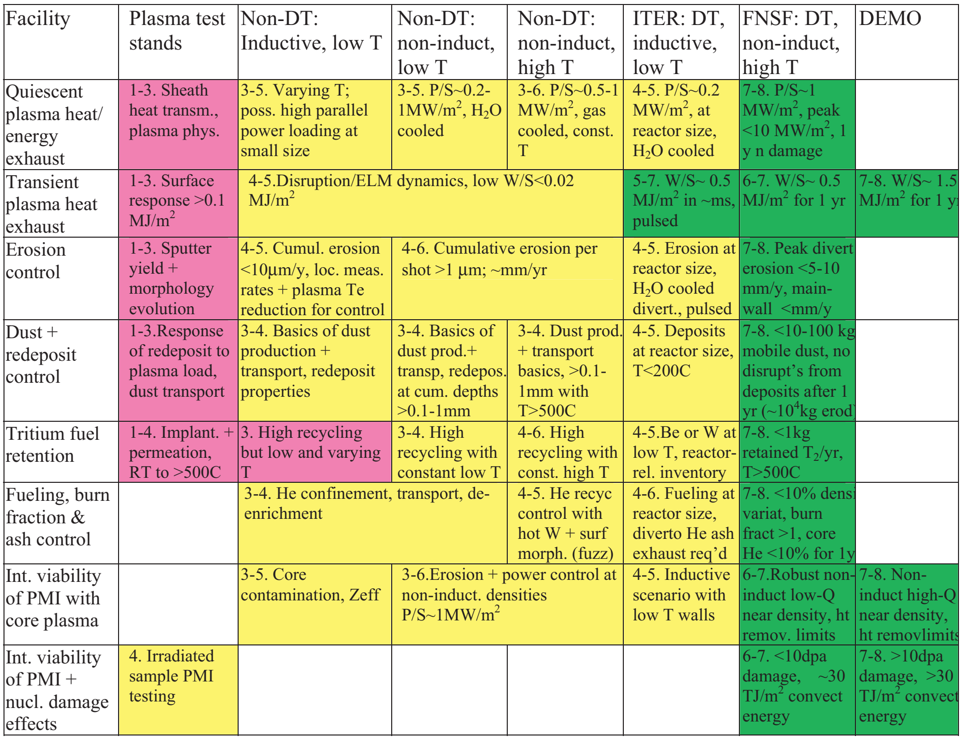
From a safety perspective, controlling tritium permeation is essential to minimize accumulation of tritium in certain areas of a fusion power system. However, the basic mechanisms of tritium adsorption and absorption at surfaces, diffusion kinetics in irradiated metals and ceramics, and the interaction with microstructural features such voids, helium bubbles, and defect clusters are poorly understood. For example, whereas the tritium retention in unirradiated materials generally decreases with increasing temperature (and the same is also observed in materials irradiated at low temperatures), neutron irradiation at intermediate temperatures where cavities are produced can lead to a pronounced increase in hydrogen isotope retention [18]. Therefore, some recent proposed approaches to develop radiation-resistant structural materials based on creation of high concentrations of He bubbles may significantly enhance tritium retention.

Additional important materials research activities include improved understanding of fundamental mechanisms controlling chemical compatibility of materials exposed to flowing coolants at high temperatures and strong electromagnetic fields [19], and exploration of the potential to utilize newly developed advanced manufacturing techniques to enable near net shape fabrication and reconstruction of intricate geometries, including ultrasonic additive manufacturing, electron beam assisted deposition, laser assisted deposition, and fused deposition modeling [20]. These advanced manufacturing techniques could enable construction of novel cooling channel geometries for improved high heat flux capabilities, and allow enhanced multi-functionality such embedded sensors in structural materials for plasma diagnostics or in situ monitoring of material degradation.

2.3. *Harness fusion energy*

The conversion of fusion power to practical electricity and the creation of fusion fuel in the blanket, tritium systems, and balance of plant regions is a complex topic involving multiple scientific phenomena. Between the PFCs, the tritium fueling, purification and recycle components and the heat exchangers, the tritium concentration and neutron flux will vary by over 10 orders of magnitude and the temperature and magnetic field will vary by several orders of magnitude, and span different regimes of physics and chemistry predominance [21]. A broad and fundamental science-based approach is needed to meet this challenge.

The magnetohydrodynamic (MHD) interactions of flowing liquid metal coolants in the strong and spatio-temporally complex magnetic field leads to highly non-linear 3D fluid physics. These MHD effects in liquid metal coolants can exceed viscous and inertial forces by five or more orders of magnitude – dominating the flow behavior and heat transfer and thereby controlling the local operating temperature, pressure, stress fields, and transport properties of the in-vessel systems. Fig. 3 compares the PbLi liquid metal flow distribution in three blanket channels with and without an applied magnetic field. An even more complex flow distribution would occur by incorporating spatial- and time-dependent variations in magnetic field. Different but similarly challenging scientific issues occur for solid breeder blanket concepts [22].



Facility	Plasma test stands	Non-DT: Inductive, low T	Non-DT: non-induct, low T	Non-DT: non-induct, high T	ITER: DT, inductive, low T	FNSF: DT, non-induct, high T	DEMO
Quiescent plasma heat/ energy exhaust	1-3. Sheath heat transm., plasma phys.	3-5. Varying T; poss. high parallel power loading at small size	3-5. P/S$\sim$0.2-1MW/m^2, H_2O cooled	3-6. P/S$\sim$0.5-1 MW/m^2, gas cooled, const. T	4-5. P/S$\sim$0.2 MW/m^2, at reactor size, H_2O cooled	7-8. P/S$\sim$1 MW/m^2, peak <10 MW/m^2, 1 y n damage	
Transient plasma heat exhaust	1-3. Surface response >0.1 MJ/m^2	4-5.Disruption/ELM dynamics, low W/S<0.02 MJ/m^2			5-7. W/S$\sim$ 0.5 MJ/m^2 in $\sim$ms, pulsed	6-7. W/S$\sim$ 0.5 MJ/m^2 for 1 yr	7-8. W/S$\sim$ 1.5 MJ/m^2 for 1 y
Erosion control	1-3. Sputter yield + morphology evolution	4-5. Cumul. erosion <10µm/y, loc. meas. rates + plasma Te reduction for control	4-6. Cumulative erosion per shot >1 µm; $\sim$mm/yr		4-5. Erosion at reactor size, H_2O cooled divert., pulsed	7-8. Peak divert erosion <5-10 mm/y, main-wall <mm/y	
Dust + redeposit control	1-3.Response of redeposit to plasma load, dust transport	3-4. Basics of dust production + transport, redeposit properties	3-4. Basics of dust prod.+ transp, redepos. at cum. depths >0.1-1mm	3-4. Dust prod. + transport basics, >0.1-1mm with T>500C	4-5. Deposits at reactor size, T<200C	7-8. <10-100 kg mobile dust, no disrupt's from deposits after 1 yr ($\sim10^4$kg erod	
Tritium fuel retention	1-4. Implant. + permeation, RT to >500C	3. High recycling but low and varying T	3-4. High recycling with constant low T	4-6. High recycling with const. high T	4-5.Be or W at low T, reactor-rel. inventory	7-8. <1kg retained T_2/yr, T>500C	
Fueling, burn fraction & ash control		3-4. He confinement, transport, de-enrichment		4-5. He recyc control with hot W + surf morph. (fuzz)	4-6. Fueling at reactor size, diverto He ash exhaust req'd	7-8. <10% densi variat, burn fract >1, core He <10% for 1y	
Int. viability of PMI with core plasma		3-5. Core contamination, Zeff	3-6.Erosion + power control at non-induct. densities P/S$\sim$1MW/m^2		4-5. Inductive scenario with low T walls	6-7.Robust non-induct low-Q near density, ht remov. limits	7-8. Non-induct high-Q near density, ht removlimits
Int. viability of PMI + nucl. damage effects	4. Irradiated sample PMI testing					6-7. <10dpa damage, $\sim$30 TJ/m^2 convect energy	7-8. >10dpa damage, >30 TJ/m^2 convect energy

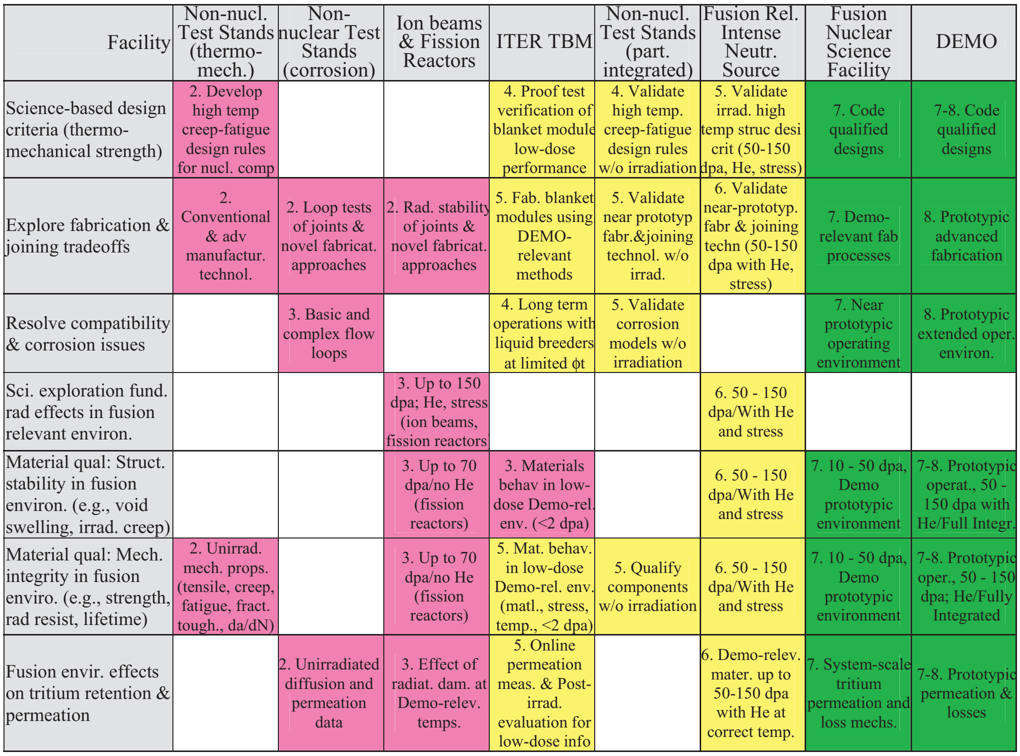
Fig. 4. Potential role of midscale and large-scale facilities to address major PMI science and technology issues. The numbers listed in each of the table entries are estimated TRL values that will be investigated with the various facilities listed at the top of the columns. Issues associated with TRL values of 1–3 are shaded red, TRL4–6 are shaded yellow, and TRL7–9 are shaded green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to harness fusion energy, it is mandatory to control the behavior of tritium in multiple materials over a broad range of concentrations and temperatures, and to identify practical approaches to simultaneously capture and convert the fusion reaction products into useful electrical power. Tritium must be handled at an unprecedented scale in fusion, with only a small fraction burned while most is exhausted from the plasma chamber and processed to recover the tritium from the helium ash and other impurities. Small batch processing (as used for tritium production in fission reactors) is not viable, given the need to breed and extract up to 0.5 kg/day from the blanket system. Flow rates of ∼5–10 kg/day must be efficiently processed over a wide range of temperatures, pressures and material conditions (where vastly different chemical science mechanisms are operative), while observing stringent accountancy and environmental release constraints. Tritium is among the most mobile of elements and can readily permeate through metallic structures, especially those at elevated temperatures with large surface areas, such as those in the heat transport system. Expected tritium release limits for fusion (<10 g/year) correspond to <0.01% of the production rate, which will require careful design of all fuel-related components. Although tritium containment in commercial fission reactors was not a crucial element of the reactor design, typical tritium release rates from fission reactors can approach ∼10% of the production rate so achieving a 1000-fold improvement in release to production ratio over fission reactors in a fusion energy plant will require improved scientific understanding of interconnected phenomena and material systems such as permeation, radiolytic chemistry, chemical kinetics, surface science, liquid metal MHD, vapor–liquid phase behavior, and mass transfer.

3. Assessment of near-term research priorities

Overall, the field of fusion nuclear sciences is in an early stage of development. A variety of innovative and high performance fusion nuclear science concepts have been proposed over the past two decades, and scoping experimental and computational research (single-effects feasibility studies) have resulted in a subset of these concepts emerging as potentially viable options for further development. Worldwide, these blanket concepts are represented by the ITER test blanket modules [23]. Each of these concepts has different feasibilities and/or performance issues as well as material requirements. Considering the current limited state of knowledge in fusion nuclear sciences, it is considered prudent for near-term research to focus on urgent single-effects and multiple-effects phenomena, with preferential emphasis on the material, technology or concept that is considered to be the most technologically mature option ("front-runner"). This focusing of research on the front-runner options that have viable extrapolation paths to successful operation in DEMO is considered to be a natural evolution in the development of advanced technologies, based on experiences from NASA programs, aerospace programs, and advanced fission reactor projects such as the Next Generation Nuclear Plant.

Technology readiness levels (TRLs) are a useful framework for quantifying the technological maturity of fusion materials, components, and systems [24]. A strategy is recommended where front-runner concepts receive the majority of available resources to move them beyond TRL3 (proof of concept) to TRL4–6 (relevant multi-effect to partially integrated environment). In some limited cases, low-TRL concepts with high potential attractiveness may be selected for prioritized R&D. The balance of resources should be used to continue the development of back up (lower TRL) options having markedly distinct feasibility issues (e.g., ceramic vs. liquid breeders) or high pay-off performance potential. An important consideration is that a threshold technical understanding (corresponding to ∼TRL5–6) is needed for a variety of fusion nuclear technology issues in order to be in a credible position (minimized mission risk) to construct a complex large-scale fusion energy



Facility	Non-nucl. Test Stands (thermo-mech.)	Non-nuclear Test Stands (corrosion)	Ion beams & Fission Reactors	ITER TBM	Non-nucl. Test Stands (part. integrated)	Fusion Rel. Intense Neutr. Source	Fusion Nuclear Science Facility	DEMO
Science-based design criteria (thermo-mechanical strength)	2. Develop high temp creep-fatigue design rules for nucl. comp			4. Proof test verification of blanket module low-dose performance	4. Validate high temp. creep-fatigue design rules w/o irradiation	5. Validate irrad. high temp struc desi crit (50-150 dpa, He, stress)	7. Code qualified designs	7-8. Code qualified designs
Explore fabrication & joining tradeoffs	2. Conventional & adv manufactur. technol.	2. Loop tests of joints & novel fabricat. approaches	2. Rad. stability of joints & novel fabricat. approaches	5. Fab. blanket modules using DEMO-relevant methods	5. Validate near prototyp fabr.&joining technol. w/o irrad.	6. Validate near-prototyp. fabr & joining techn (50-150 dpa with He, stress)	7. Demo-relevant fab processes	8. Prototypic advanced fabrication
Resolve compatibility & corrosion issues		3. Basic and complex flow loops		4. Long term operations with liquid breeders at limited ϕt	5. Validate corrosion models w/o irradiation		7. Near prototypic operating environment	8. Prototypic extended oper. environ.
Sci. exploration fund. rad effects in fusion relevant environ.			3. Up to 150 dpa; He, stress (ion beams, fission reactors)			6. 50 - 150 dpa/With He and stress		
Material qual: Struct. stability in fusion environ. (e.g., void swelling, irrad. creep)			3. Up to 70 dpa/no He (fission reactors)	3. Materials behav in low-dose Demo-rel. env. (<2 dpa)		6. 50 - 150 dpa/With He and stress	7. 10 - 50 dpa, Demo prototypic environment	7-8. Prototypic operat., 50 - 150 dpa with He/Full Integr.
Material qual: Mech. integrity in fusion enviro. (e.g., strength, rad resist, lifetime)	2. Unirrad. mech. props. (tensile, creep, fatigue, fract. tough., da/dN)		3. Up to 70 dpa/no He (fission reactors)	5. Mat. behav. in low-dose Demo-rel. env. (matl., stress, temp., <2 dpa)	5. Qualify components w/o irradiation	6. 50 - 150 dpa/With He and stress	7. 10 - 50 dpa, Demo prototypic environment	7-8. Prototypic oper., 50 - 150 dpa; He/Fully Integrated
Fusion envir. effects on tritium retention & permeation		2. Unirradiated diffusion and permeation data	3. Effect of radiat. dam. at Demo-relev. temps.	5. Online permeation meas. & Post-irrad. evaluation for low-dose info		6. Demo-relev. mater. up to 50-150 dpa with He at correct temp.	7. System-scale tritium permeation and loss mechs.	7-8. Prototypic permeation & losses

Fig. 5. Potential role of midscale and large-scale facilities to address major issues for nuclear degradation of materials and structures for the first wall, blanket and vacuum vessel. The numbers listed in each of the table entries are estimated TRL values that will be investigated with the various facilities listed at the top of the columns. Issues associated with different TRL values are shaded red (TRL1–3), yellow (TRL4–6), and green (TRL7–9). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

machine such as a Fusion Nuclear Science Facility (FNSF, nuclear technology testing device [25]) or DEMO.

Fusion research prioritization should consider the key feasibility issues of a concept in a comprehensive integrated manner to identify the research elements that are essential for a successful next step device. For example, the optimized tritium extraction method depends on the type of tritium breeder used. The utilization of systems-level guidance as part of the R&D prioritization process is considered to be a natural and necessary step in order for fusion nuclear technology to progress from its current status of single-effects concept exploration research toward multiple-effect synergistic phenomena research needed to establish the proof of principle for fusion plasma-facing, blanket, and energy- and fuel-conversion concepts.

3.1. *Roles of computational modeling and midscale and major experimental facilities*

In nearly all fusion nuclear science topical areas, computational modeling is not yet sufficiently advanced to enable stand-alone predictive results to be obtained in the absence of experimental data. For example, state-of-the-art first principle materials models are currently limited to simulation sizes of <1000 atoms due to many-body effects that must be included in the solution of the Schrödinger equation for atomic interactions (resulting in a scaling of order N^6 for truly first principles condensed matter physics models). Conversely, the number of atoms involved in a single isolated energetic displacement cascade event associated with neutron irradiation exceeds 1 million atoms, and much larger simulation sizes are needed to address microstructural features and stochastic events. Similarly, molecular dynamics simulations using fitted interatomic potentials (rather than true first principles methods) are limited to time scales of ∼1–10 ns, whereas key diffusional interactions require time scales exceeding milliseconds. Consequently, in general all research scenarios should involve some aspect of experimental validation, i.e., computational modeling alone is not yet considered to be an appropriate proxy for experiment. As a corollary, experimental exploration without utilization of computational models to guide the test formulation and interpretation is also not recommended.

Most of the facilities currently being used for fusion technology studies are small- to medium-scale facilities that were constructed in the previous century. As such, many of these fusion technology test stands are insufficient without upgrades to perform the more sophisticated exploratory research needed to establish scientific proof of principle for fusion energy. The experimental portions of the next stage of fusion nuclear science research are anticipated to be performed predominantly in dedicated medium scale fusion technology facilities, as outlined in Section 3.2.

3.2. *Key facilities for fusion nuclear science research*

A DEMO or intermediate-step FNSF will be the first fusion device in which (1) the plasma pulse will extend to days–weeks–months, 2) both plasma loading and nuclear loading are integrated together, (3) the very long time-scale issues of PFC lifetime and plasma duration will be seen (including dust, debris, material migration), (4) continuous plasma exhaust and rapid turn-around fueling will be needed, and (5) long timescale tritium behavior in the plasma chamber – PFC – blanket environment will be observed. Providing these features in present and currently planned experimental facilities is not possible and therefore acquiring the knowledge needed to confidently design, build and operate an FNSF/DEMO should utilize a multi-pronged scientific research program involving linear plasma devices, toroidal confinement devices, and a series of offline non-nuclear and nuclear testing facilities. Linear plasma devices can provide long uninterrupted exposures of materials to a range of plasmas, with varying degrees of integrated effects, although missing the toroidal geometry and a number of self-consistent features. The toroidal confinement devices are required to simulate the actual magnetic geometry and associated plasma flows and core-scrape off layer-material wall couplings with limited durations, while not at the full plasma parameters expected in a FNSF/DEMO. Offline facilities (i.e., high heat flux) can provide the engineering tests necessary for basic materials and integrated material and coolant solutions, as well as fission reactors and a fusion relevant neutron source for neutron irradiation effects.

To date, no fusion blanket or power extraction system has ever been built or tested. Appropriate next-step midscale tritium breeding and energy capture facilities depend on the specific breeding blanket concept selected. For liquid metal breeding systems such as PbLi, a multi-effect Blanket Thermomechanical, Thermofluid MHD Test facility would bring together simulated surface and volume heating and reactor relevant magnetic fields with test mockups having prototypical size, scale, materials operated at prototypical flow rates, pressures and temperatures for extended periods. The experimental program would investigate performance and failure rates as well as modes and effects under increasingly integrated conditions. Similarly, a Tritium Breeding and Extraction Facility comprised of a neutron source and breeding module coupled to a tritium extraction system (e.g., a liquid metal breeder loop in a fission test reactor) could explore multiple-effect engineering issues for tritium transport and processing. These facilities would compliment information gained in the ITER TBM program where blanket module operations can be studied in a full fusion environment including nuclear heating, but where exposure times are limited dedicated tritium purification and recycle facilities are also expected to also be needed to address fundamental phenomena such as chemical reaction rates, separation factors, hydride storage capacities, materials compatibility, analytical techniques and confinement effectiveness.

In combination with ITER and theory/simulation, the midscale facilities summarized in the preceding two paragraphs will provide the experimental database to extrapolate knowledge to the FNSF/DEMO regime.

Fig. 4 summarizes the potential role of various facilities to resolve key PMI issues. An analogous chart was prepared for PFC development issues [1]. The majority of the work should be focused on solid-wall W-based PFCs since these are the current leading candidate approach. Backup options of exploring either carbon-based solid materials due its lack of melt damage or liquid metals to remove high divertor heat loads should be considered if the W-based approach is found to be unworkable, as well as optimized divertor magnetic configurations. The near-term research would utilize plasma test stands, non-DT short pulse confinement experiments, and non-DT long pulse confinement experiments. Many of the divertor and PMI issues could be studied by working first at low wall temperatures. Such work would likely advance most of these issues to the TRL4–5 stage. Extending these studies to high wall temperature in non-DT long pulse devices, combined with ITER experience, could advance our understanding for most issues into the TRL5–6 range. Ultimately, experiments in a DT-based long pulse FNSF could advance the understanding to the TRL7–8 levels necessary to confidently move to a DEMO scale device.

Fig. 5 highlights the contribution of key facilities for investigating structural materials issues. Estimates of the attainable TRL within a given facility for each issue are represented numerically and by color-coding of cells. Some midscale facilities involve testing of the materials in the thermal-mechanical and coolant corrosion environment anticipated for a fusion reactor, but without the neutron irradiation exposure. Several neutron irradiation facilities are envisioned to address the issue of materials property degradation due to accumulation of displacement damage and transmutation products. Fission reactors and accelerator-based irradiation sources provide a good simulation of neutron-induced displacement damage and bulk-heating effects. Accelerator-based sources also permit simultaneous exploration of displacement damage and gas effects, and for specific situations enable investigation of multiple-effects such as in situ measurement of tritium production and release in ceramic breeders. On the other hand, it should be noted that large-volume plasma-based irradiation sources are needed to carry out fully integrated materials and component level testing. Non-plasma irradiation sources are not suitable for investigating the synergistic effects that occur in many other fusion components. Since non-plasma sources are comparatively low cost relative to plasma devices, they serve an important role in reducing the significant costs and risks associated with fully integrated, multiple variable tests performed in plasma devices.

It is worth noting that none of the materials issues advance beyond TRL2–3 by conducting single-effects experiments in non-nuclear test stands or ion-beam/fission reactor facilities, i.e., these issues cannot be resolved without performing experiments in partially or fully integrated test facilities. Another important conclusion is the limited benefit, from a materials science perspective, obtained from ITER TBM. The panel concluded that valuable fabrication R&D would be obtained from the ITER TBM development program, but the low neutron fluence available in ITER is of limited value for resolving nuclear degradation of materials issues except possibly some insights in specialized ceramics such as SiC flow channel inserts that will reach swelling saturation. The panel concluded that performing scientific experiments in partially integrated non-nuclear test stands, coupled with materials science irradiation studies in a midscale fusion-relevant neutron source, is the most effective near-term pathway for reaching intermediate TRLs for structural materials.

4. Recommendations and conclusions

There are inherent inefficiencies and costs associated with exploring multiple materials or concept options once the technological maturity has grown beyond the concept exploration stage (TRL1–3). Thus research to explore the scientific proof of principle (TRL4–6) for fusion energy is most expediently accomplished by focusing research activities on the most technologically advanced option.

In order to appropriately position the technological maturity of PFCs, materials, blanket, and tritium technology for potential next step devices following ITER, it is imperative to initiate or enhance modest research activities on fusion nuclear technology. Numerous opportunities for high-impact fusion research may be achievable by making modifications to existing facilities and/or moderate investment in new medium-scale facilities. In particular, linear plasma device(s) might be profitably used to explore critical length scale and edge physics relationships that strongly affect redeposition of sputtered materials in plasma facing components; an intense neutron irradiation facility might be used to explore new variations of computationally designed ferritic steels that could provide sufficient resistance to degradation from fusion neutrons; one or more tritium science facilities could explore viable mechanisms to efficiently and reliably extract tritium from hot coolants and examine other chemical science issues; and a non-nuclear thermohydraulic/MHD facility might explore the complex fluid interactions and flow perturbations in fusion-relevant coolant channels and magnetic fields.

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