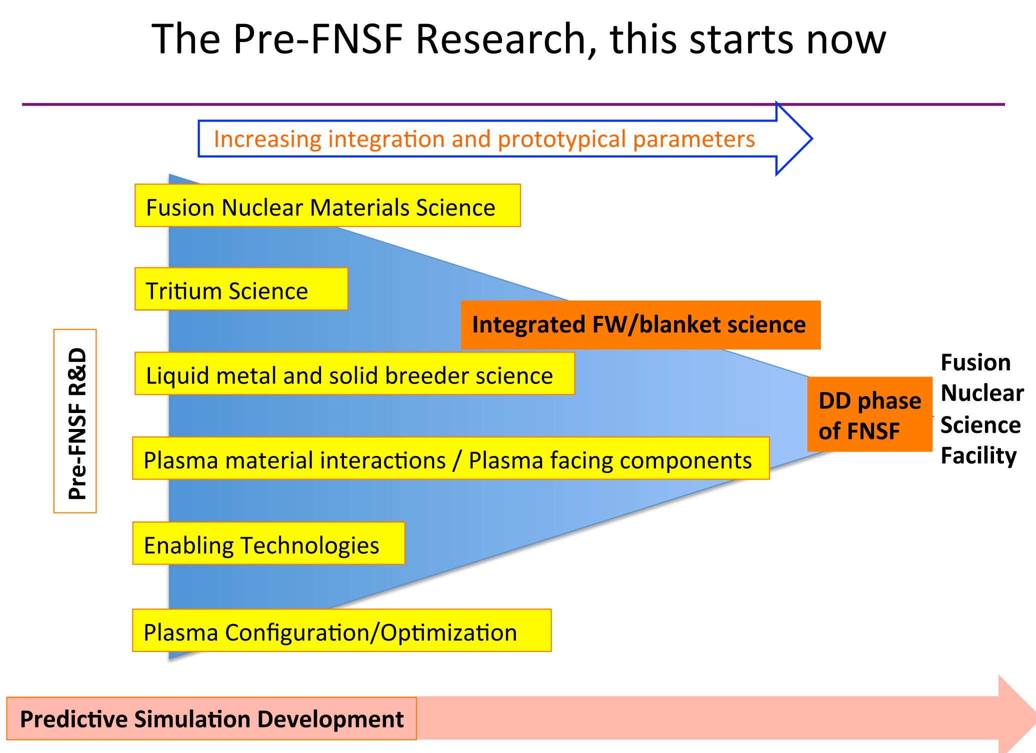
Pre-FNSF Research and Development

C. E. Kessel, Princeton Plasma Physics Laboratory

Research and development (R&D) are required to establish a basis for the design, construction, and operation of a fusion nuclear science facility (FNSF). Whatever the actual time-scale for a FNSF is, it drives the R&D over a broad technical scope including fusion nuclear materials science, liquid metal (and solid) breeder science, tritium science, plasma material interactions, enabling technologies, and plasma science development. This is schematically illustrated in Fig. 1. In parallel, the computational simulation tools must be developed and expanded through a cycle of theoretical development and experimental validation. The first four topics are considered the most critical for fusion development because they pose significant barriers to fusion's success if they are not resolved to a sufficient degree. A number of previous studies have identified needed general R&D for the progress in fusion nuclear science, materials, and plasma materials interactions [1-4].



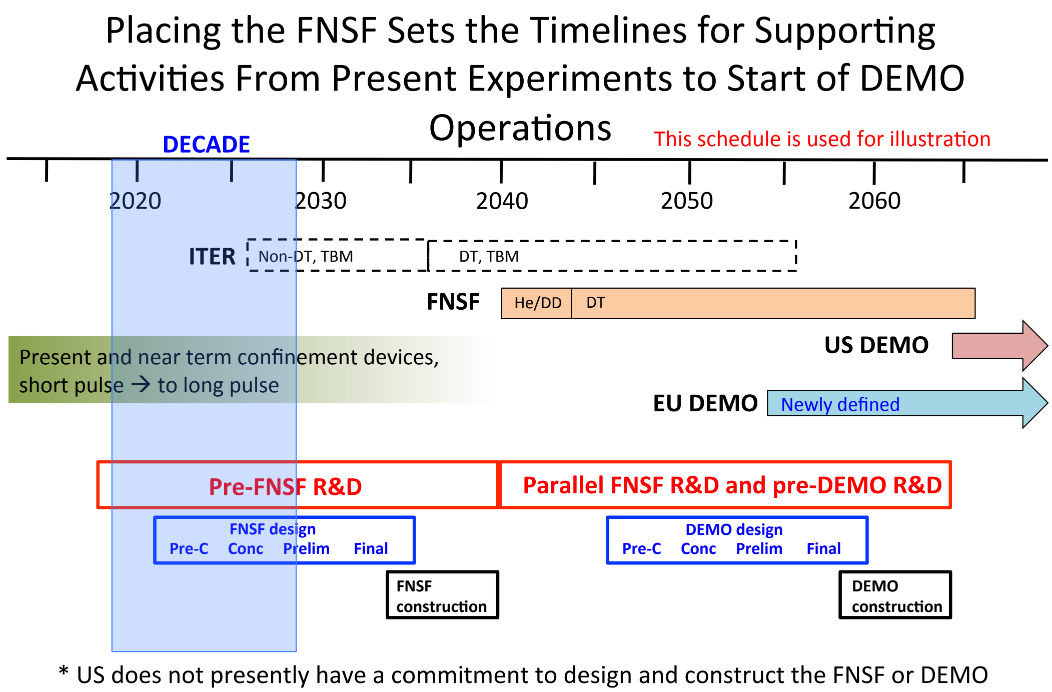


Figure 1. Illustration of the primary pre-FNSF R&D areas to support the design, construction and operation of a fusion nuclear science facility (FNSF). The tritium and breeder science areas converge into the blanket science area as integration progresses, and the PMI/PFC area converges on the DD phase of a FNSF for ultra-long plasma pulse lengths. Lower plot is a notional timeline where the timeframe for the FNSF operation sets the pre-FNSF R&D timing, as well as the relationship to other devices such as present confinement devices, ITER, US DEMO, and parallel-FNSF R&D activites.

Figure 1 shows a timeline with a FNSF beginning in 2040 and lasting until 2066. The pre-FNSF R&D extends from today to this start date, along with the FNSF design and construction. After the FNSF operation begins, the R&D continues as development continues in parallel with the facility as a consequence of its results and in support of its multiple phases. A decade from the present is noted to show an important phase of research in the US that must take place to develop the knowledge and confidence that a FNSF can succeed in its mission. Focused activities on the first four topical areas is critically needed to provide the scientific foundation for projecting behavior in the fusion nuclear regime.

Fusion nuclear materials science

Fusion nuclear materials science includes the development of structural and functional materials that have resistance to nuclear damage and phenomena associated with transmutation gases, He and H. It also includes the use of low radio-activation materials that lead to low nuclear waste ratings, and operation at high temperatures and relatively high coolant pressures typical of fusion designs. These materials range from the fusion core out to the vacuum vessel, and in some cases can include the cryostat, the TF magnet, or other lifetime components near the fusion core. As an example, for the dual coolant lead-lithium (DCLL) primary blanket in the FESS-FNSF design[5], the materials include

Reduced activation ferritic martensitic (RAFM) steel (multiple variants)
SiC-composite flow channel insert (multiple variants)
Tungsten in some form for the divertor and FW (multiple variants)
Bainitic steel for the vacuum vessel and low temperature shield
WC and borated ferritic steel shield filler
LiPb liquid metal breeder/coolant
He coolant
H_2O coolant in a low temperature shield, outside the vacuum vessel

The variants for the RAFM steel refer to cast nano-structured alloys (CNA) and oxide-dispersion strengthened (ODS) versions that enhance radiation resistance and provide the materials with greater creep rupture strength at high temperatures [6]. The variants for SiC-SiC composite as a flow channel insert, and tungsten for the divertor are for illustration, mainly stemming from a much weaker knowledge of what the best material form is for the fusion environment. A FNSF would advance the materials as it raises the neutron fluence and raises the operating temperature in each DT phase of its operation.

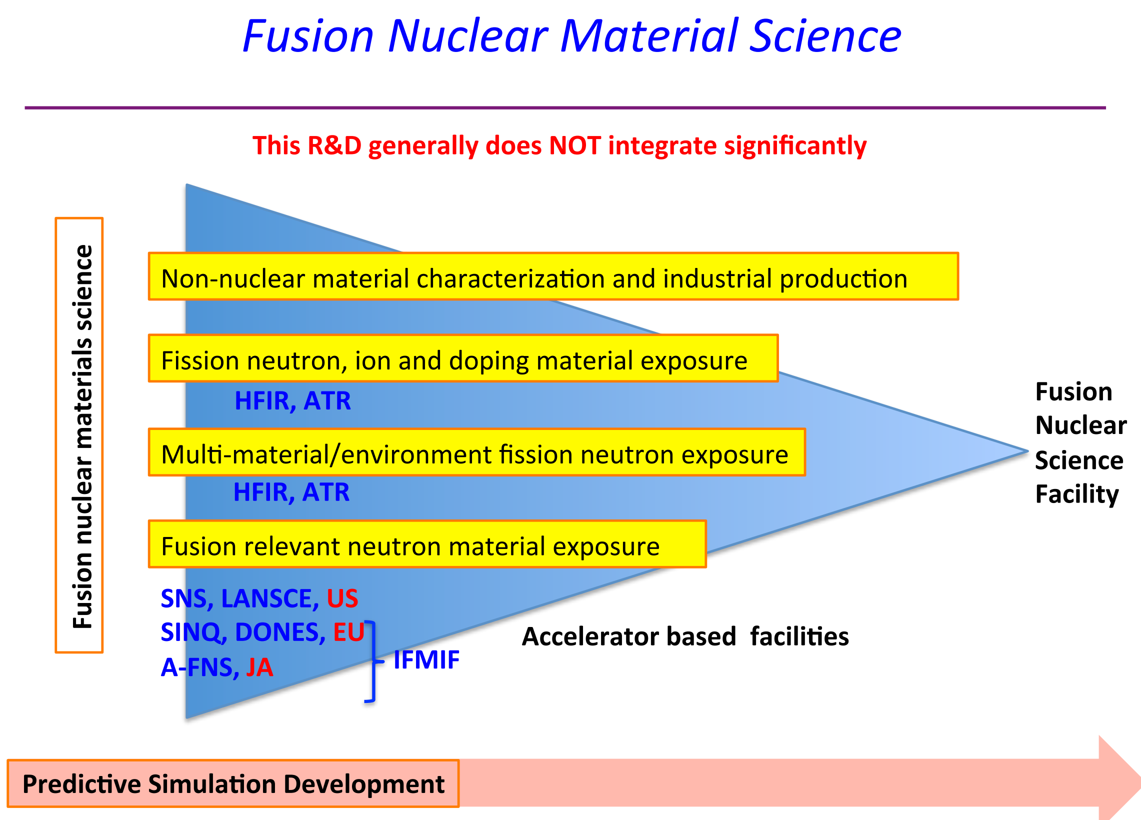


Figure. 2. A schematic description of the major fusion nuclear material elements, highlighting non-nuclear, fission nuclear, multi-material, and fusion relevant nuclear testing. It is difficult to combine this individual material testing with other more integrated testing described later.

The program to develop and qualify materials for a FNSF includes the non-nuclear characterization, fission nuclear testing (and ion beam and/or doping), fusion relevant nuclear testing (e.g. IFMIF, DONES, [7]), industrial material production and manufacturing of components from these materials, and a material/environment optimization, shown in Fig. 2. Depending when a FNSF begins its operation, it then requires fusion core components for the specific phase it is operating, but also near-fusion-core lifetime components, like the vacuum vessel, from the beginning of operation. The intervening time scale must be adequate to provide the facility with its pre-FNSF qualified components. The philosophy taken for the FESS-FNSF [5] has been that all materials in the fusion core and near core must be qualified as individual materials, up to the neutron fluence they will experience, with a fusion relevant neutron source. In addition, all components in the fusion core will have highly integrated non-nuclear testing at the prototypical parameters of the blanket, divertor, or other apparatus (e.g RF launcher), which will occur during that phase. This is illustrated in Fig. 3, where the FNSF has been assumed to start in the year 2040 and end its operation at 2065. Short black arrows mark the beginning of a phase that will reach the noted material peak damage (dpa) level. Below this are the fusion core components, composed of materials listed earlier for the DCLL blanket. For illustration purposes and consistency with the program described [5], three RAFM variants arrive at the beginning of different phases, and similarly for the other materials. The RAFM steels are phased to arrive for higher operating temperatures and higher neutron fluence. The bainitic steel vacuum vessel arrives at the beginning of the facility operation as it must, as do all the life of plant materials near the fusion core but outside the vacuum vessel. It should be emphasized that the articles being delivered to the FNSF are functioning industrially produced components, not individual materials.

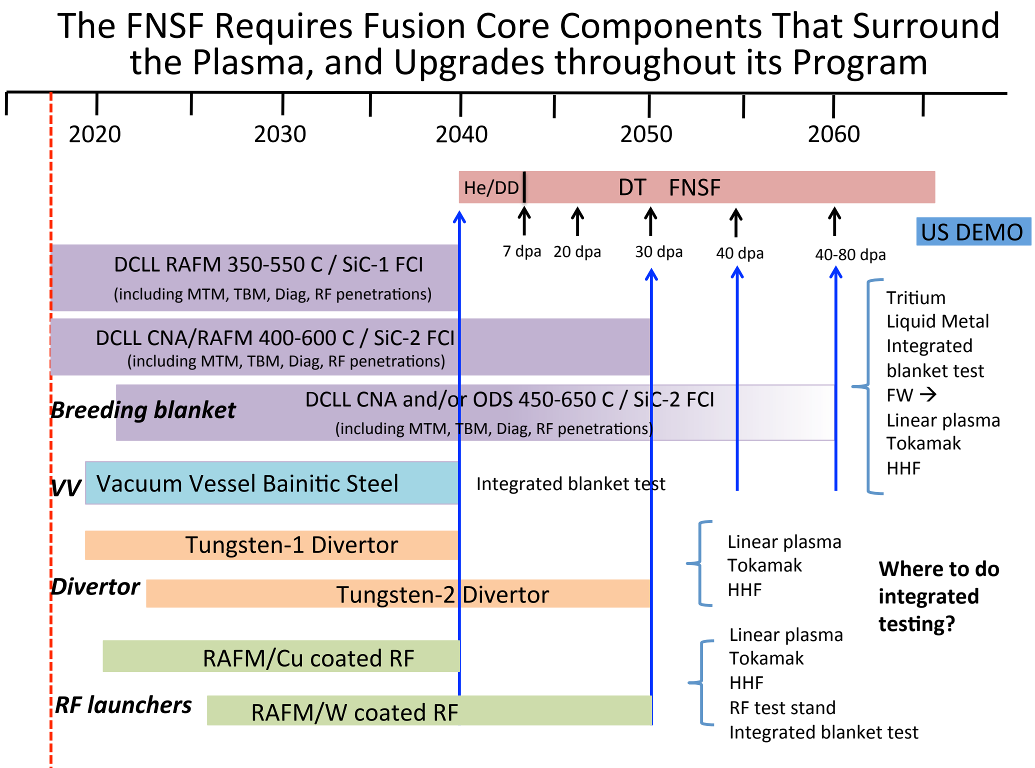


Figure 3. A time-frame showing how fusion core components for the DCLL blanket require development time in order to arrive at the FNSF as industrially produced articles, with the required qualification of fusion relevant neutron exposure and integrated non-nuclear testing of components.

Figure 3 briefly offers some insights into the non-nuclear integrated test evolution. Here the components are pictured arriving at the FNSF at the appropriate time, as qualified under their integrated test program, which can involve multiple facilities. The DCLL blanket components are qualified initially in early tritium and liquid metal breeder partial integration experiments, but ultimately are tested as a complete component in a blanket test facility. However, the first wall, which is part of the blanket and which is a plasma facing component, would require some separate testing in linear plasma, tokamak and high heat flux facilities. The divertor and RF launcher components would also receive integrated testing in these PFC test facilities. The RF launcher would likely be tested in a dedicated RF test stand, but also in the integrated blanket test facility. The bainitic steel could be the vacuum chamber structure for the blanket testing facility.

Materials development and qualification actually permeates all the topical areas in fusion research. As shown in Fig. 1-3, the development of materials, and the components made from them, begins in the pre-FNSF R&D on separate paths, one leading into the fission and fusion relevant neutron exposure of individual material samples, and the others leading into the non-nuclear testing. The non-nuclear testing entails tritium behavior science and liquid metal breeder science, which converge into integrated blanket, divertor, or other apparatus testing. The plasma facing materials have their own R&D

path that involves testing in plasma exposures and non-nuclear integrated tests, but must also be tested in nuclear exposures. The FNSF itself provides the unique total fusion environment and will provide a new and more relevant materials database upon which the DEMO and power plants can be designed. During the FNSF program the fusion core components are removed and cut into material samples for a wide range of examinations to characterize this in-service material response. In addition, a material test module is used in the blanket region of one of the sectors to provide surveillance samples, as well as surveillance samples placed at life of plant components (e.g. VV) for periodic examination. In parallel with the FNSF, materials development must continue to provide the needed components as the FNSF program evolves, and to prepare for a DEMO facility.

Tritium science

A FNSF would be the first fusion step to target tritium self-sufficiency, producing enough tritium to compensate consumption, decay, and losses. This tritium is produced in the breeder, which is inside the fusion core. The FESS-FNSF would produce about 10 kg of tritium per year during the later DT phases (averaged over the phase). In addition, approximately 15-80 times this amount must be cycled through the plasma fueling and exhaust system due to the tritium burnup fraction, estimated for FNSF [5] to be 1.3-6.4%. The significant requirements of self-sufficiency and low plant tritium losses to the environment (< 1 g/year) requires very precise knowledge of tritium behavior in a wide range of materials and component environments (e.g. temperature, surface interfaces). It is virtually impossible to stop tritium (hydrogen) from moving through materials, however controlling its movement is possible. Although the behavior of tritium in a fusion system is governed by physical chemistry at a basic level, the actual environment aggravates and complicates this tremendously. The experimental data on various tritium properties used to calculate its behavior (e. g. diffusivity, solubility, and surface dissociation and recombination rate coefficients) have large variations, due to practical system variations, such as the condition of a surface, or inherent difficulties in measuring very small amounts of non-radioactive hydrogen isotopes. The resulting impact on the amount of tritium that could be lost can be 50x [8], based on simulations to explore this impact. The neutron irradiation environment will significantly aggravate properties, and likely generate synergies that must be understood to the extent possible, such as enhanced trapping of tritium in solid material due to damage or even the nanostructured particles introduced to enhance the material's radiation resistance. It is necessary to account for its location and concentration (inventory) throughout the fusion core and plant. The major activities in the tritium science area include its behavior in materials and multi-materials, its behavior at the plasma material interface, its extraction from the LiPb breeder material, and some access to its behavior in irradiated materials and multi-materials via fission (or fusion to the extent possible) irradiation. As the tritium experiments become more integrated and prototypical they will be combined with the liquid metal (or solid) breeder thrust leading to the blanket component testing.

Liquid metal breeder

The DCLL blanket relies on the $Li_{15.7}Pb_{84.3}$ eutectic liquid metal as a coolant and a breeder. This breeder choice is motivated by the desire to avoid neutron degradation of solid breeders under neutron irradiation and high temperatures, to avoid the use of beryllium for neutron multiplication, to have weaker interactions with oxygen under potential accident conditions (versus pure Li), in-situ control of tritium breeding ratio through Li-6 fraction control, in-situ constituency control of the breeder, and to use the breeder as a coolant. The behavior of conducting liquid metals in a magnetic field is very complex, and interactions with multiple materials will provide an extreme challenge for a fusion system. Understanding of the breeder flow behavior in a magnetic field under heating, high temperatures, corrosion and mass transport, and gas production and transmutation (breeding tritium produces He) has not been established, and can not be simulated in arbitrary geometries. Three main areas for the liquid metal breeder require R&D, MHD thermo-fluid phenomena, LiPb interaction chemistry and mass transport, and the electrical and thermal insulator flow channel insert required for the liquid metal cooling to be feasible, with strong physical coupling among these features. The movement from single effects experiments to greater levels of integration and prototypicality would focus on operating temperatures, magnetic field, proper geometric flow orientations, and larger test sections.

It should be noted that the FESS-FNSF [5] study assumed that RAFM steel and He-cooled blanket concepts were the proper focus for long term fusion power plant relevance. In addition to the DCLL blanket, alternates were carried in the R&D program that addressed the most vulnerable aspect of the DCLL blanket, which is the breeder. It is proposed that the helium cooled lead-lithium blanket (with much slower moving liquid metal Pb-Li breeder which removes the liquid metal MHD complexities) and the helium cooled pebble bed (solid ceramic breeder material with neutron multiplier, which removes the liquid metal altogether) be included in the FNSF testing program as test blanket modules. The breeder R&D before the FNSF can be included in the US program or gathered from collaborations with international partners. Water is not considered a power plant relevant coolant for fusion [9].

Ultimately the tritium and liquid metal thrusts must converge into a non-nuclear integrated blanket testing facility and program, where sufficiently large prototypes, or full size, fusion core components, produced by an industrial source, can be tested with as many prototypical features as possible. For the DCLL blanket, this would include helium coolant at ~ 8 MPa, LiPb at ~ 2-3 MPa and ~ 10 cm/s flow speeds, with deuterium introduced as a surrogate for tritium, utilizing strip or embedded heaters to approximate volumetric heating, surface heating on the first wall, accessible magnetic fields ($\geq$ 5 T), and significant instrumentation. Peripheral systems are required to maintain a prototypical environment such as deuterium removal from the breeder, heat exchangers for both coolants, LiPb and He cleanup and constituency control, and artificial introduction of He (by-product of neutron reactions with Li when tritium is produced) into the LiPb. Tests of full sectors, or penetrated sectors (TBM, MTM, RF launchers, diagnostic ports) would be examined with their associated apparatus. For example, in the case of RF launchers a dump would be required to absorb the wave power in order to see the launcher in operation with the surrounding blanket simultaneously. This highly integrated testing at the appropriate operating temperatures and operating time is required before each phase in a FNSF program, and serves as one of the primary qualification criteria for fusion core components.

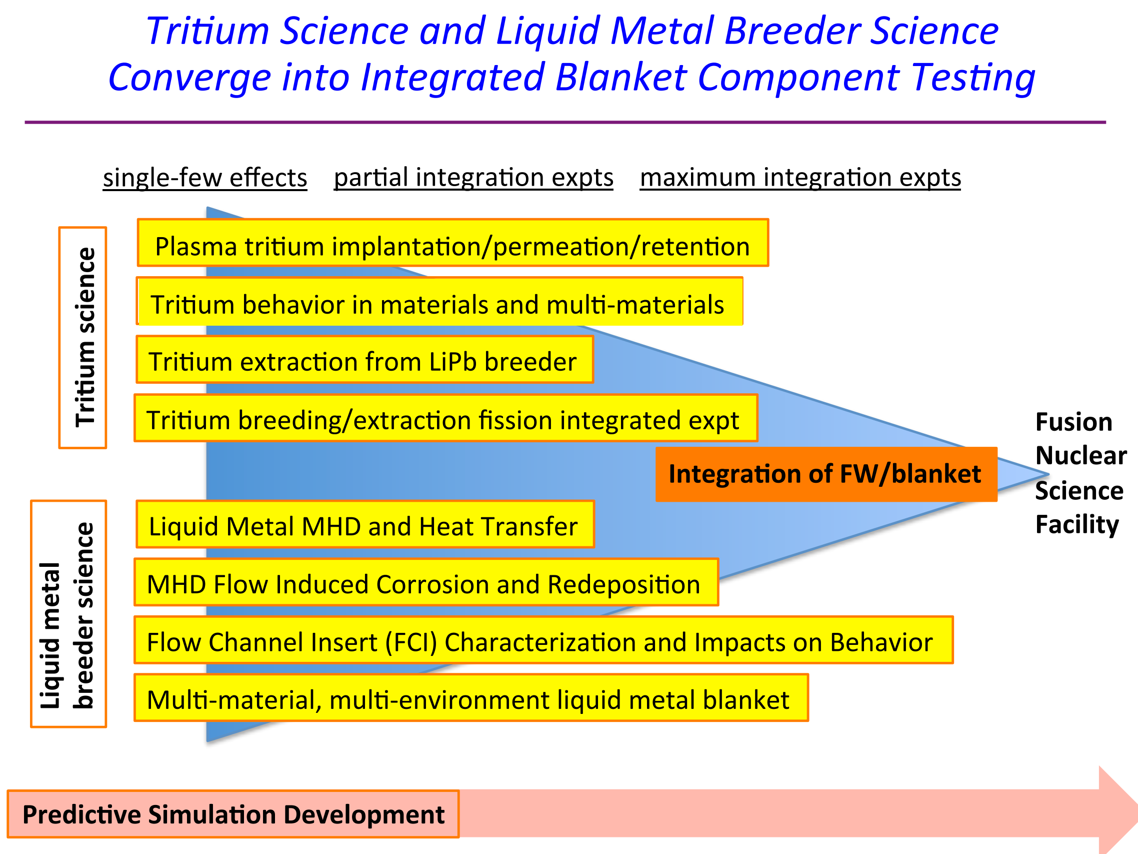


Figure 4. Schematic of the highest priority pre-FNSF R&D program elements in the tritium science and liquid metal breeder science areas, converging into the integrated blanket science.

Plasma material interactions

Simultaneously, other integrated environments are required, particularly for those fusion core components that are plasma facing, such as the divertor, RF launchers, and diagnostic ports. These components must be tested, to the extent possible, in tokamaks and linear plasma facilities with as prototypical loading as accessible. The highest heat fluxes may only be accessible in dedicated high heat flux facilities without plasma. This leads to the fourth primary R&D thrust on plasma material interactions (PMI) and plasma facing components (PFC). In a FNSF the plasma pulse length will reach weeks, and the PFCs will experience the combined plasma and nuclear loading, and gives rise to the long time scale issues of dust and debris generation, material erosion/re-deposition/migration, plasma facing material re-constitution, and tritium retention. The FNSF will require continuous fueling and exhaust of the plasma with rapid turnaround for fuel recovery and re-injection to minimize tritium inventories. The two primary regions are the FW (e.g. blanket, RF launchers, diagnostic port) and the divertor, each characterized by their specific heat and particle fluxes, particle energy spectra, plasma and neutral densities, potential transients, geometries, plasma facing materials, and cooling/structure designs. R&D into the material and component design/development requires complete plasma side loading specifications which are identified as 1) steady state heat flux, 2) steady state particle flux, 3) blobs (turbulent transport across SOL), 4) ELM transient heat and particle loading, 5) mitigated disruption heat, particle, and electromagnetic loading, and 6) erosion/re-deposition/migration and re-constitution evolution from plasma material interactions. The precise prescription for all of these is lacking, and continued efforts to characterize these loads are needed. This material and design element of the R&D must pursue credible integrated solutions, integrated with the blanket (or launcher, etc.) and cooling requirements, as well as actual plasma environments [10]. The components would be tested in tokamaks with relatively short pulses, and linear plasma facilities for ultra-long exposures. There is a level of integration accessible with fission and/or fusion relevant neutron exposures, by taking these material samples after neutron irradiation and using them in linear plasma devices for long plasma exposures. This has recently been performed with material samples from HFIR fission neutron exposures placed in the tritium plasma exposure in TPE at INL [11].

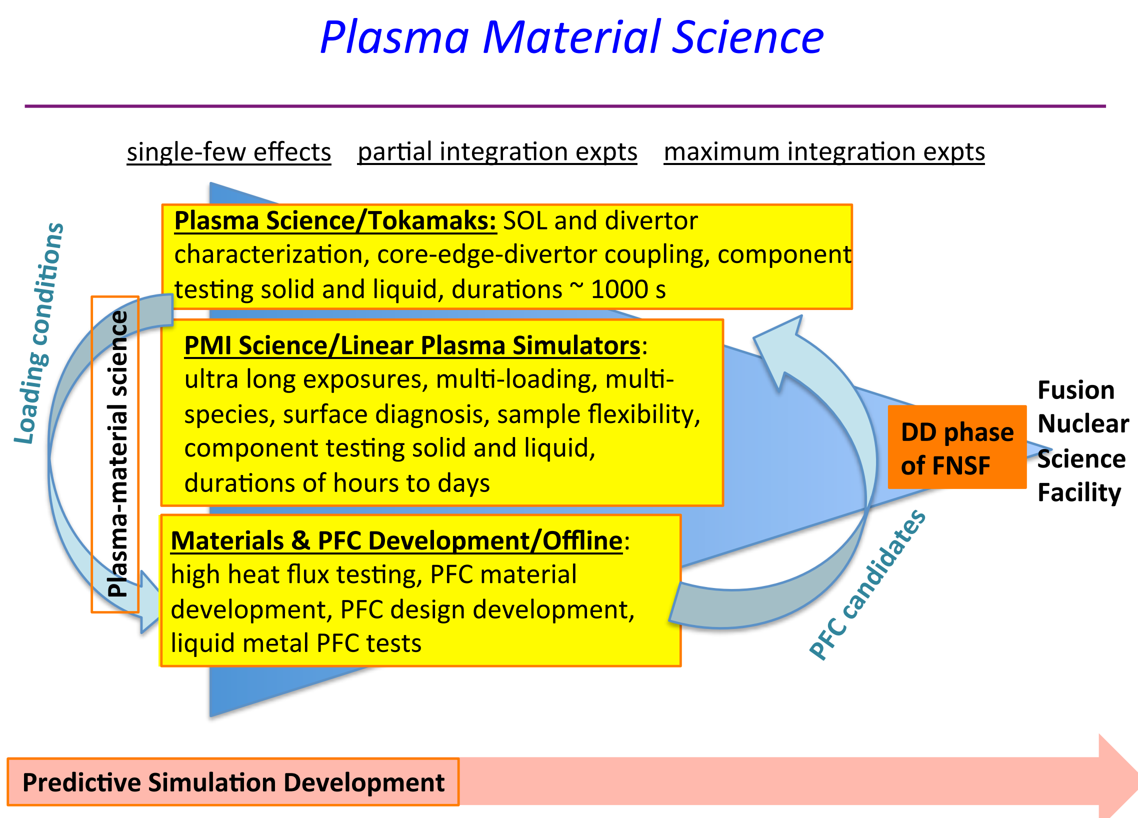


Figure 5. A schematic showing the PMI/PFC pre-FNSF R&D, culminating in the DD phase of the FNSF where ultra-long plasma pulses are created. The interplay between tokamak and linear plasma facilities in providing the testing environments for materials and PFC components is critical for successful development of solutions for a FNSF.

The very long plasma pulses targeted in a FNSF are beyond those plasma pulse lengths anticipated in present and future facilities, as we know them now (e.g. ITER), and this is illustrated in Fig. 6. The EAST tokamak has a goal of 1000 s, and ITER's advanced tokamak scenarios are intended for 3000 s pulse lengths. The DD phase in the FNSF has the primary goal of developing the longest pulse lengths anticipated in the FNSF program from the existing tokamak database at the time it begins operation. A plasma pulse extension program going from one hour plasma pulses to two week long plasma pulses was constructed in order to estimate time-frames for this phase of the program. The DD phase of the facility is ideal for this pulse length extension because all support systems are steady state and remote handling and maintenance (nuclear ready) are already integrated in the device's design. To some extent, the pulse length extension is repeated in the DT phase due to the stronger nuclear loading, but may be accelerated based on the DD experience. The development of predictive simulation for the PMI/PFC physics and engineering is critical to bridge this gap and avoid long program delays on the FNSF, and would be relied upon heavily in design of the FNSF PFCs.

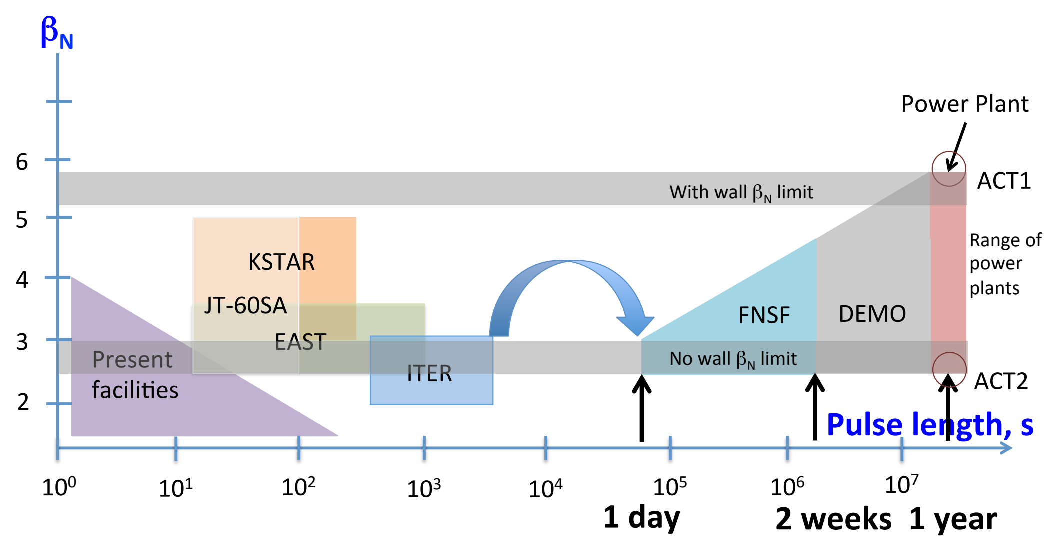


Figure 6. An illustration of plasma performance (β_N) versus the plasma pulse length, showing the general decrease with progressively longer duration in present facilities, and the multiple long pulse facilities pursuing this regime. ITER, is the only burning plasma facility with long pulses, and a very large gap from these devices to the ultimate pulse length of ~ 2 weeks in a FNSF, or ~ 1 year in a power plant.

Enabling technologies

Enabling technologies is a topic that contains several critical support science and technology areas, including (but not exhaustive) magnets, heating and current drive, plasma fueling and exhaust, diagnostics, helium cooling, disruption mitigation, tritium processing, the cryo-plant, and heat exchangers. A FNSF simply would not operate without all of these subsystems (and many not listed), so they are fundamental to reaching mission goals for the facility. As such, they must be advanced to provide the required performance and fully steady state operation. Most of these have achieved considerable advancement in the ITER program, although extended capability for next step facilities has been identified for many systems [4]. The heating and current drive and diagnostics areas are also plasma facing or near plasma and require more extensive testing and material qualification before they can be installed on a FNSF. The enabling technologies R&D must continue during and even beyond the FNSF in order to serve the needs of an electricity producing DEMO. For example, the balance of plant equipment, developing high efficiency systems for plasma heating and current drive, and improving the ancillary systems in the fusion plant based on FNSF experience are essential for the longer term. Fig. 7 shows a schematic view of the enabling technology area in preparation for a FNSF.

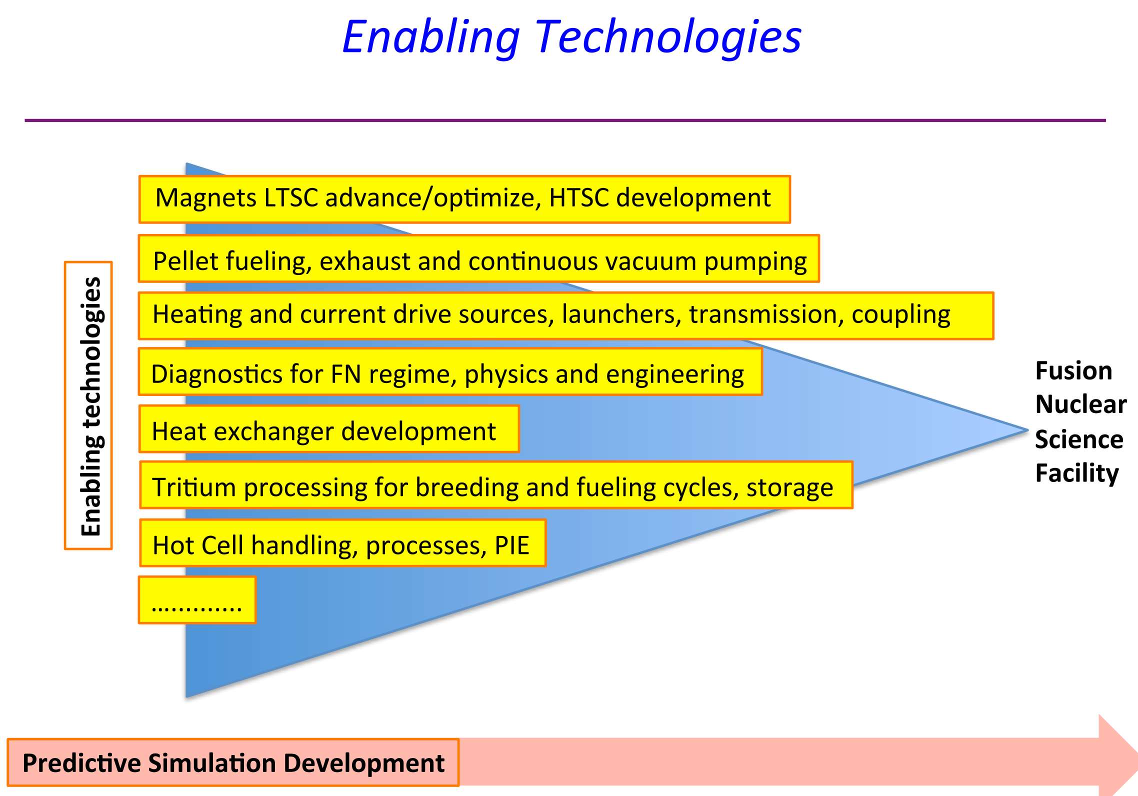


Figure 7. Schematic view of some of the critical enabling technologies that must be advanced in preparation for a FNSF. Many have been strongly advanced in ITER, but the fusion nuclear environment requires re-focus and further advancements.

Plasma science

Plasma development centers around demonstrating attractive plasma scenarios for the FNSF operating space, shown in Fig. 8. Only ITER can provide a burning plasma scenario, however, its 100% non-inductive and higher beta scenarios may be limited, or delayed in its program. The long pulse DD (EAST, KSTAR and JT-60SA) experiments would be the platforms for pushing into this regime, and simulations would be required to extrapolate to the DT burning operation. It should be emphasized that the mature shorter pulse tokamaks have much to contribute to exploring and identifying credible scenarios for the FNSF, particularly because of the integration aspects. Plasma scenarios for the FNSF are characterized by core plasma parameters such as 100% non-inductive current, β_N, n/n_{Gr}, f_{BS}, q_{95}, shape, pedestal, core profiles, and collisionality. But in addition, they should be described by metallic plasma facing walls (W/RAFM), plasma to wall distance ($\geq$ 10 cm), a high density radiating divertor, feedback for error fields and/or resistive wall modes, ELM suppression, or other boundary conditions that can strongly affect the core configuration and performance. Demonstrating the simultaneous core and edge solutions for long durations (> several core plasma current relaxation times) is the basis that is sought for the FNSF operating scenario.

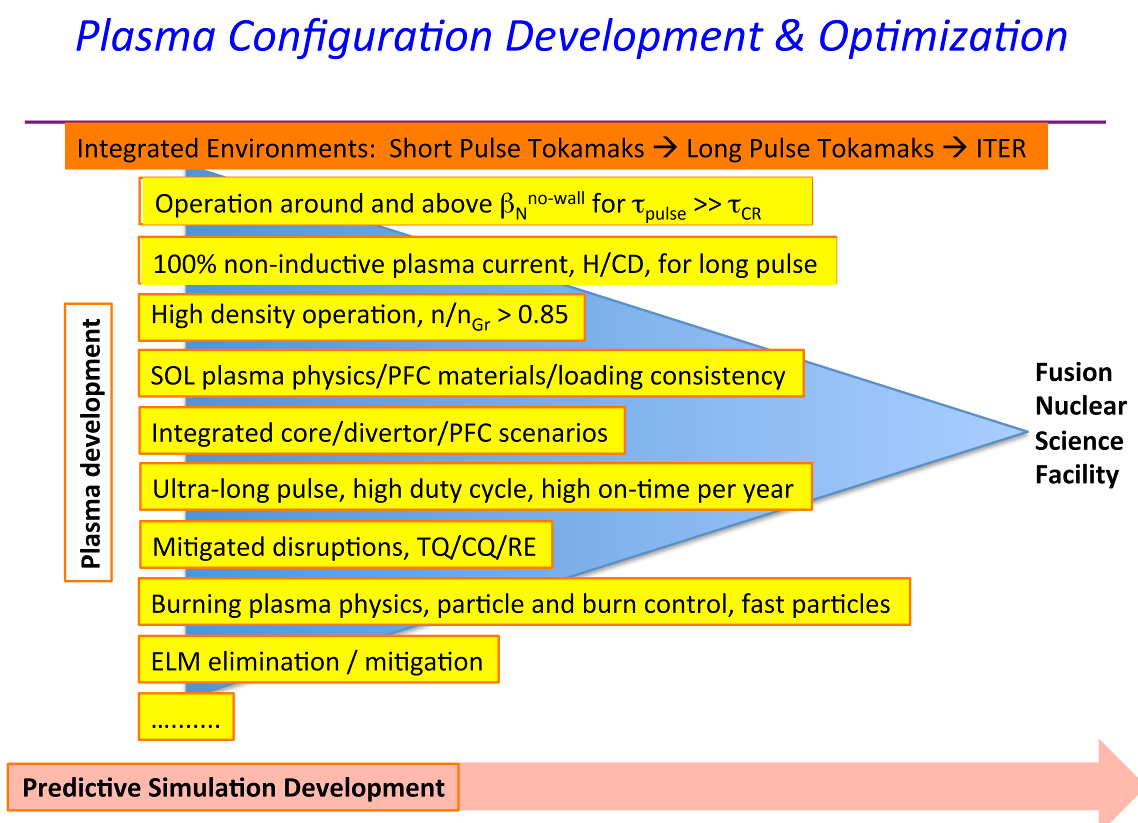


Figure 8. A schematic of the numerous core and SOL/divertor plasma characteristics that must occur simultaneously in order to produce a high performance plasma for ultra-long durations in a FNSF.

<u>Initiatives in the US MFE Program</u>

The first strongly fusion nuclear confinement device, often referred to as a Fusion Nuclear Science Facility (FNSF), will provide the penultimate step in the convergence of fusion plasma and fusion nuclear science. The US fusion program view has considered this “smaller” step as a prudent strategy prior to a demonstration power plant (DEMO) due to the extreme fusion nuclear environment, the complex integration of components with their environment, and the coupling of plasma physics and nuclear science. The purpose of the FNSF is to operate with ultra long plasma pulse lengths and very high duty cycles, with completely integrated fusion core components (e.g. blanket, divertor, shield, vacuum vessel, magnets), and in the fully integrated environment of fusion neutrons, volumetric and surface heating, hydrogen in materials, strong magnetic fields, pressures/stresses, high temperatures, vacuum interface with plasma material interactions, and flowing breeder with materials interactions, all with significant gradients. In this respect, the FNSF continues the materials testing in the complete fusion environment. It is also useful to consider the landscape of facilities and time-scales, to clearly identify the next decade, and at least conceptually a FNSF operation and both the pre-requisite and parallel offline facilities to support it. Fig. 1 shows a notional timeline from 2015 to 2065.

The research and development to establish the technical basis for a decision to propose construction of a FNSF is dominantly within the next decade, and subsequent activities provide highly integrated component non-nuclear testing and continue the fusion nuclear single-few effect material testing. The time-line shown for the FNSF is uncertain and will depend on many factors. Since the lead time to resolve fusion nuclear science readiness issues may be long, it is important to move forward now on those issues that represent potential show-stoppers, and in particular for the U.S. to act in those areas where it is, or can be, the world leader. Affordable basic science initiatives in selected areas could markedly improve our readiness to propose a FNSF 10 years from now.

US leadership can be established in the R&D topics listed above through a careful assessment and commitment to infrastructure and focused problem solving. International collaborations will be required to complete the basis for any fusion nuclear facility as all the expertise and facilities are not in the US. These R&D topics will significantly support individual institutions (e.g. universities, national labs) and demand their cooperation, while leading to industrial engagement, as they must for a facility to be pursued.

Integrated studies of this facility must continue as the basic science elements (listed above) are studied, incorporating new understanding and new developments, while maintaining a level of constraint imposed by the integrated nature of such a facility. The predictive simulation development, so critical to the legacy of fusion research, must simultaneously progress to establish the needed level of prediction capability and for use in integrated studies of future facilities. The predictive simulations must evolve to include greater physics scope, physics fidelity, physical system representation, and integration of synergistic phenomena, true both for plasma physics and engineering science. ***Any strategic plan for fusion research must include the entrance to the fusion nuclear regime, and the associated R&D program, if fusion energy is a program goal.***

[1] FESAC Priorities, Gaps and Opportunities: Toward a Long Range Strategic Plan for Magnetic Fusion Energy, FESAC Report, DOE/SC-0102, 2007 available at https://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf.

[2] *Research Needs for Magnetic Fusion Energy Sciences,* DOE/OFES Planning Report, 2009, available at https://science.energy.gov/~/media/fes/pdf/about/Magnetic_fusion_report_june_2009.pdf .

[3] C. E. Kessel et al, Fusion Nuclear Science Pathways Assessment, Princeton Plasma Physics Report PPPL-4736, 2012.; http://bp.pppl.gov/pub_report//2012/PPPL-4736-abs.html.

[4] S. Zinkle et al, FESAC Report "Materials Science and Technology Research Now and in the ITER Era", http://science.energy.gov/~/media/fes/pdf/workshop-reports/20120309/FESAC-Materials-Science-final-report.pdf.

[5] C. E. Kessel et al, "Overview of the Fusion Nuclear Science Facility, a Credible Break-in Step on the Path to Fusion Energy", Fusion Eng. Des, 2017, https://doi.org/10.1016/j.fusengdes.2017.05.081

[6] A. F. Rowcliffe et al, "Material Challenges for the Fusion Nuclear Science Facility", Fusion Eng. Des., 2017, https://doi.org/10.1016/j.fusengdes.2017.07.012.

[7] A. Ibarra et al., *Fusion Sci. Technol*. **66** (2014) 252.

[8] F. Franza et al, IEEE Trans. Plasma Science, **42**, (2014), 1951.

[9] M. S. Tillack et al, "The Use of Water in the Fusion Core", Fusion Eng. Des., **91**, 2015, 52.

[10] US MFE PMI Workshop Report, 2015, https://science.energy.gov/~/media/fes/pdf/workshop-reports/2016/PMI_fullreport_21Aug2015.pdf

[11] B. J. Merrill, M. Shimada, and P. W. Humrickhouse, J. Plasma Fusion Res., **10**, (2013), 71.