Interim Status of ReNeW Thrusts

Forward

The objective of the ReNeW project is to provide input to OFES for their use in developing a plan for US fusion research during the ITER era, roughly the next two decades. The ReNeW activity will culminate in a Report to OFES that will be completed shortly after the ReNeW Workshop, to be held in June 8-13, 2009. The report will use as its framework a set of approximately 15 research thrusts. Here the words "research thrust" are used to describe an organized, multi-faceted attack on some question, or coherent set of questions, essential to magnetic fusion energy science and technology, using a combination of new and existing program elements.

A series of workshops was held during the month of March, 2009, one workshop for each of the five ReNeW themes. Those workshops featured open community discussions of the research requirements to address the open gaps and issues identified in the ReNeW resource documents. Open discussion of potential research thrusts occurred at these workshops, as well

This document is a compilation of the interim status of ReNeW research thrusts at a point in the process following completion of the Theme workshops. There has been little or no attempt at integration of the thrusts to date, and much more discussion and work is planned to strengthen and improve the coherence of the overall package for the final report. The interim Thrusts, though not final in either number or precise content, are the products of significant effort by the Theme groups and community contributors. They are being made public at this stage to facilitate further discussion and feedback.

The (approximate) Theme Titles comprise the main headings of this report, e.g. "1." while the Thrusts themselves (21 at this time) comprise the second-level headings, e.g. "1.1".

CONTENTS

1. Burning Plasmas & ITER

The next frontier for magnetic fusion is the study of burning plasmas. The ITER facility, to be operated as an international project, will bring research efforts into this new, grand-challenge regime. The ITER research program will have two primary needs: 1) Ensuring that ITER will fulfill its baseline operation and 2) Supporting demonstration of extended operation in ITER, in preparation for next-step device(s). Hence, the proposed wrap-categorization of thrusts for Theme 1 is based on these two overarching needs.

1.1. Provide physics basis and maximize physics output for ITER baseline operation

ITER baseline operation is focused on achieving the technical performance objectives of Q = 10 for discharges that last 300-500 seconds. This first thrust category is organized into three groups of research activities.

1.1.1. Mission critical solutions

Disruptions. Characterize and predict/avoid/mitigate disruptions (and runaway electrons)- Disruptions and runaway electrons pose significant design and operational challenges because they cause electromagnetic and thermal loading. In order to eliminate their threat, research is needed to improve the predictions of disruption onset and runaway electron generation, to design active methods for avoiding disruptions, to develop reliable mitigation schemes, and to characterize disruption dynamics with validated models. Work is also needed to find disruption-tolerant plasma-facing components.

ELMs. Control ELMs- Edge Localized Modes could cause damage to the divertor and first wall. Research is needed on how ELMs could be controlled with non-axisymmetric magnetic fields or through other means (pellet pacing, vertical jogs, oscillating magnetic fields, etc.)

Tritium retention and dust. Mitigate plasma-wall interactions in the specific areas of tritium retention and dust- Research is needed to develop methods for removing tritium from plasma-facing components in ITER and to avoid dust buildup.

1.1.2. Specific research issues

Wall conditioning, high-Z materials. Mitigate plasma-wall interactions in the specific areas of discharge cleaning/wall conditioning and qualification of high-Z refractory materials- Here, the issue is to develop methods for ITER first wall preparation, discharge cleaning, between-shot wall conditioning, and disruption recovery. Also, research is needed to examine the effect of the melt layer on the capability of high-Z refractory metal PFCs to remove heat.

Assess fast ion stability and transport and the impact on the plasma and first wall- The focus here would be to achieve predictive understanding of fast-ion collective instability thresholds, profile redistribution, and fluence of lost fast ions to the divertor and plasma-facing components.

Discharge scenarios. Develop ITER-relevant scenarios (for breakdown ramp up, flat top, and ramp down) in H, He, D, and DT plasmas- Research is needed to improve simulations of ramp-up and ramp-down scenarios, especially in regimes with dominant electron heating, for the various plasma targets that are planned for ITER operation.

Study transport (especially the L-to-H mode transition) in ITER-like conditions (e.g., low torque, Ti = Te, etc.)- Existing tokamaks would be upgraded with the tools necessary to reproduce, study, and control plasma conditions as similar to those in ITER as possible. Under these conditions, an integrated campaign would be carried out to validate models for H-mode transport and the pedestal.

Core transport validation. Establish a center for core transport validation- This center would use results from state-of-the-art diagnostic capabilities on a suite of existing plasma devices in order to perform validation and achieve predictive capability, especially for anomalous electron and ion thermal losses.

1.1.3. Essential tools and capabilities

Diagnostics. Develop innovative diagnostics for the burning plasma environment- The demanding thermonuclear environment of a burning plasma device such as ITER brings new challenges and risks for measurement systems. The focus here would be on developing new diagnostic techniques that are capable, compatible, and reliable, along with real-time ability to analyze and interpret measurements for physics understanding and plasma control.

Control. Ensure a reliable control system for burning plasmas- This research activity comprises several aspects of research and development for control systems, ranging from assessment of actuator and diagnostic requirements, to validated control models and algorithms, and testing of control approaches on operating devices.

Burn control / isotopic fueling. Control the burn (e.g., isotopic fueling)- Theory, experiments, diagnostic development, simulations, and control methods would be used to determine particle transport, pellet ablation, and fuel deposition for the purpose of stabilizing the burn and determining tritium retention.

RF launcher-PFC-plasma interactions. Understand the interaction of RF waves, plasma, and plasma-facing components in the scrape-off layer region- The issue here is to understand the physics of ICRH antenna interactions with plasmas, high voltage breakdown and mitigation, impact of RF sheaths, and long-distance coupling, so that ICRH can become a reliable heating technique for ITER.

1.2. Demonstrate ITER enhanced operation in preparation for DEMO.
ITER enhanced operation is focused on achieving the technical performance objectives of Q = 5 for 3000-second discharges. For this second thrust category, research activities from the first thrust category (such as investigations of specific burning plasma research issues, further development of essential tools and capabilities, etc.) would be carried forward. In addition, several other thrust/research activities would be involved:

1.2.1. Steady state operation modes.
Develop predictive understanding of hybrid and advanced-tokamak steady state operation modes. Research is needed on how to use current drive tools for creating sufficient off-axis current in order to maintain or access specific current profiles that are required for hybrid operation or advanced-tokamak steady state operation, and to achieve predictive physics understanding of these processes.

1.2.2. Alpha particle control.
Devise controls for alpha particles to achieve improved fusion performance- This research would develop avoidance or amelioration techniques for alpha losses that are projected to be unacceptably high and thus expand the stable operating regime with optimized heating, current, and flow profiles.

1.2.3. Small-ELM and/or ELM-free operational regimes
Develop small-ELM and/or ELM-free operational regimes- The research here would assess whether small-ELM operating regimes can be used reliably and whether ELM-free operational regimes (e.g., QH mode) can be developed with good heat confinement but without density or impurity buildup.

2. Creating predictable, high performance, steady state plasmas

The state of knowledge must be sufficient for the construction, with high confidence, of a device that permits the creation of sustained plasmas that meet simultaneously, all the conditions required for practical production of fusion energy.

2.1. Controlling and sustaining fusion plasmas.

How high performance a fusion plasma can be controlled and maintained for an unlimited period of time?

This broad, cross-cutting Thrust includes is aimed at squarely and definitively addressing one of the most critical issues for tokamak research: To what extent can the promise of advanced tokamak scenarios, with high pressures and high fractions of self-generated current, be realized in practice under fusion-relevant conditions, while reliably avoiding disruptions and other damaging transients? Since it is by no means assured that the performance limits will be as high as desired by reactor designers, a parallel effort would be conducted to assess the potential performance, and transient events, of non-axisymmetric configurations. These can operate steady-state without current-drive and appear to have less virulent off-normal events as they approach their operating limits.

Panels involved: Control and Off-Normal events (Theme II applications, going beyond ITER requirements and including 3-D configurations), Auxiliary Systems (actuators for Control), parts of Measurement panel (sensors, and real-time capability for interpretation and analysis), small part of Validated Predictive Modeling (reduced models for control).

Potential cross-links: Strong links to Theme I. Strong connection to Integration Thrusts 5-7. Assessments of non-axisymmetric configurations and control techniques have clear synergy with Theme V.

2.2. Predictive capability

Can the complex, multi-scale phenomena of fusion plasmas be understood and predicted, through advances in theory and simulation and comparison with detailed measurements?

Panels involved: Validated Predictive Modeling (including developments in theory as well as simulation), and Measurement (development of improved diagnostics for existing experiments to enable model validation).

Potential cross-links: This Research Thrust could be joint with Theme I and will include ITER predictions as a goal; it could for example incorporate the 'Center for Validated Understanding of Core Transport' proposed by Theme I Confinement panel. It would also contribute to the PWI panel of Theme III. Open to discussion whether it should also cover Theme V concepts.

2.3. Measurements for burning plasmas:

Advance measurement capability for the harsh fusion environment to enable the success of ITER and control of steady state fusion plasmas.

Panels involved: This is part of the Thrust originally proposed by the Measurements panel: "Development of the Capability, Compatibility, Calibration, and Reliability for ITER and for SS DEMO". It would include development of both new and more robust techniques for the fusion environment, and measurement of newly important quantities such as dust and alpha distributions. This would be a relatively small and highly focused, though long-term, effort to meet identified gaps which would not otherwise be addressed. "The measurements enable the mission!"

Potential cross-links: Proposed as a joint Thrust for Themes I and II. May potentially contribute to Themes III and IV if PWI/PFC diagnostics, and engineering instrumentation, are included. Note that other diagnostic development, for physics understanding and for control, is included in Thrusts 1 and 2.

2.4. Advanced magnets for fusion:

Can high temperature superconductors and other magnet innovations be exploited to advance fusion research?

Panels involved: Magnets panel. As with Thrust 3, this would be a focused effort aimed at enabling or advancing the missions of other Thrusts. Basic research on HTS would lead to high current conductors and then be integrated into fusion-capable structural components.

Potential cross-links: This enabling Thrust would broaden the range of options for experimental fusion research in all Themes. Potential examples include: Higher magnetic field, lower cost magnets for Theme II Integration experiments; Integration of flexible HTS tapes into conductors and structures with complex shapes to ease the manufacture of steady-state magnets for 3-D and other alternate configurations (Theme V); Demountable joints in superconducting coils to enable experimental facilities in which internal components can be removed and replaced remotely (Themes II, III and/or IV). Research activities would therefore be reassessed later in the ReNeW process once physics research needs have been clarified and prioritized.

2.5. Integrated dynamics of burning plasmas

How will the complex, coupled dynamics of the core burning state evolve as the self-sustained limit is approached?

Panels involved: Integration panel, strong connection with Control, and Predictive Capability thrust among others. This thrust would focus on issues of core plasmas with dominant self-heating and self-driven current, without necessarily meeting DEMO-relevant edge conditions.

Potential cross-links: Strong connection, and potential opportunity for combination, with Theme I Thrust on 'ITER enhanced operation in preparation for DEMO'.

2.6. Core-boundary integration

How do sustained plasmas with high energy flow interact with their material interfaces? Using this understanding, what is the optimal solution for both sustainment and power handling?

Panels involved: Integration panel, again with strong connections to other Theme II panels. This Thrust would focus on physics issues involving both the core and SOL/PFCs, and include integration of DEMO-prototypical boundary conditions with a steady-state, fusion-relevant, but not necessarily burning, core. Like Research Thrust 1, this aims to address a critical issue for fusion: *Can the heat loads be handled while simultaneously maintaining an attractive, steady-state core?*

Potential cross-links: This Research Thrust would need to rely on strong parallel efforts on Plasma-Wall Interactions, innovative divertor solutions and PFC materials from Theme III. Potential opportunity for combination.

2.7. Steady-state, alpha-dominated plasmas

Can the knowledge gained in each of the above Research Thrusts be integrated to demonstrate confidence in a steady-state, alpha-dominated plasma which is attractive for producing fusion energy)

Panels involved: Integration panel, again with strong connections to other Theme II panels. This "final integration" Thrust would need to combine the challenges of the preceding two Thrusts, either experimentally or by using improved predictive capability.

Potential cross-links: This would again connect strongly with Theme III, adding neutron issues. Because it could involve strong neutron flux and fluence, there may also be opportunities for joint activities with Theme IV.

3. Taming the Plasma Material Interface

3.1. Understanding the Plasma Scrape-off Layer

How can we extrapolate the observed PMI interactions in existing fusion devices to ITER and beyond?

The existing data on the variation of plasma scrape-off layer characteristics with core plasma conditions and magnetic configuration predict a variation of the e-folding length for power flux at the outer mid-plane in ITER from 5 to 25 mm. There are also substantial variations in the predicted power flow to the divertor and the particle flux magnitude and profile. The ITER design is based on the worst case predictions and leads to aggressive Plasma Facing Component designs with little margin for off-normal events. Moreover, in the past decade at least a dozen new facets of SOL behavior have been uncovered, suggesting that our understanding of the physics is significantly incomplete. We need an aggressive program of new or more complete diagnostics of the plasma edge on a variety of fusion devices coupled with an innovative theory and modeling effort to understand the plasma scrape-off layer. Gathering the necessary knowledge will require increased plasma experiment time dedicated to understanding the SOL. Understanding gained over the next 5 years would reduce the risk for ITER and enhance the results from ITER.

3.1.1. Plasma Edge Database

Research Need	Work Description	Expected Outcome
Limited database on plasma edge characteristics on any fusion device	Deploy additional or new diagnostics to understand plasma flow, temperature, density, electric field, etc.	Detailed consistent database suitable for calibration and validation of plasma edge models

3.1.2. Validated predictive SOL models

Research Need	Work Description	Expected Outcome
Plasma edge modeling is limited by loosely coupled codes that do not include all relevant effects	Improve coupling of codes and develop first principles turbulence and cross field transport including plasma materials interactions	Create models that explain the SOL observations and can predict future device plasma edge parameters

3.1.3. RF heating – Plasma edge compatibility

Research Need	Work Description	Expected Outcome
RF power injection is observed to generate local hot spots on PFCs but the mechanisms are poorly understood	Develop reliable and verified techniques for computing self-consistent heat and particle flux in the edge and to PFCs	Improved RF coupling, reduced peak heat loads to PFCs, reduced plasma contamination

3.1.4. Plasma-facing material modifications

Research Need	Work Description	Expected Outcome
Plasma facing materials are modified by plasma impact and some new surface structures have been discovered on refractory materials. The formation mechanisms and erosion characteristics are not understood.	Upgrade or construct new laboratory facilities to study the new surface structures over a wider range of plasma parameters and measure erosion. Develop improved models of surface modification and erosion of complex surfaces.	Understanding of plasma modification of materials relevant to future fusion devices and the impact of those modifications on the edge and core plasma.

3.1.5. Diagnostics for the fusion environment

Research Need	Work Description	Expected Outcome
Many existing core diagnostics depend on mirrors or similar components placed near the plasma. The impact of plasma or neutron bombardment on those components will require innovative modifications for future fusion machines.	Develop or innovate new concepts to qualify materials or components for internal diagnostic components including cooling and bonding techniques	Robust reliable diagnostic components for future fusion machines that can be tested on existing devices.

3.1.6. PFC Performance

Research Need	Work Description	Expected Outcome
The performance of PFCs on existing machines is poorly understood because of a lack of performance diagnostics on most devices	Initiate PFC diagnostic development in laboratories and deploy the diagnostics on existing devices	Detailed understanding of the performance of PFCs and their response to normal and off-normal operation to provide the boundary conditions for SOL and erosion modeling.

3.2. PMI research in highly controlled, well-diagnosed dedicated facilities

How can we understand the complex multi-scale phenomena that regulate plasma materials interactions in fusion devices?

Plasma materials interactions vary by many orders of magnitude depending on temperature, particle species, fluence, hydrogen and helium content, material composition, and exposure time. PMI research has revealed many previously unknown phenomena such as radiation enhance sublimation, chemical erosion, blistering, particle pumping and release, and formation of nano-scale fuzz. While some of these phenomena are reasonably well understood, some are newly discovered and have no adequate physical model. It is crucial to understand PMI because the material response alters the plasma edge and plasma core. Most existing fusion machines have inertially cooled PFCs and the surface temperature varies either as square root time or linearly with time. Data on PMI from those machines is also integrated over several shots and often varying plasma conditions. We need controlled laboratory experiments under fusion relevant conditions to accurately measure material changes. Those measurements will be used to develop first principles models to predict material response under conditions in future fusion machines.

3.2.1. PWI Modeling

Research Need	Work Description
The processes governing PWI span time scales from 10^{-14} to 10^{3} seconds and our understanding is at best rudimentary. Model development requires precision control and diagnosis of plasma experiments	multi-scale modeling, 'steady-state' highly controllable plasma and surface parameters, Testing of irradiated materials and elevated temperatures, steady state and pulsed. Testing of virgin and irradiated materials at normal and elevated temperatures, with steady state and pulsed plasma bombardment

3.2.2. PFC development

Research Need	Work Description
New PFC designs and materials needed because we are at margins of feasibility	PFC development and testing Testing PFC performance for long pulses at high temp.

3.2.3. Nuclear capable RF antennas

Research Need	Work Description
Designing nuclear capable RF antennas	testing and validation of large scale components and new materials for coils Testing large scale components for long pulses at high temp.

3.2.4. Dust

Research Need	Work Description
Dust formation from PMI with internal components not understood	Evaluate the anticipated contribution to dust formation from the materials selected for ICRF & LH antenna front ends

3.3. Innovations to improve power and particle handling

Can we create new PFC materials or edge plasma configurations to improve power removal capabilities or reduce erosion of PFCs?

The majority of fusion devices do not have actively cooled PFCs. ITER will have carbon, tungsten or beryllium joined to water cooled copper heat sinks. Emerging long pulse fusion devices are also planning to use similar structures. The preferred PFC structures for future fusion devices are helium cooled refractory structures or flowing liquid surfaces. Either option will require near term research to develop new materials compatible with the fusion environment, fabrication and joining techniques that will yield robust components, thermal fatigue testing of innovative solid components to verify performance, and/or liquid surface experiments and modeling to verify compatibility with fusion devices.

3.3.1. Refractory alloy development

Research Need	Work Description	Expected Outcome
Existing refractory alloys lack either the fracture toughness or thermal conductivity for PFCs	Develop innovative refractory alloys with high thermal conductivity and resistance to neutron embrittlement with activiation compatible with fusion energy	Nano-composite refractory alloys (W or Mo or …) with stable DBTT and increase recrystallization temperature and adequate fracture toughness.

3.3.2. Heat sink development

Research Need	Work Description	Expected Outcome
Helium gas cooled heat sinks are either very complex or have high pressure drop making them difficult to use in fusion devices	Develop innovative refractory heat sinks with high heat removal capacity, low pressure drop, reasonable fabrication cost, and joining methods for attaching refractory PFMs. Conduct laboratory qualification tests before deployment on fusion devices.	Robust high temperature components with adequate capacity for off-normal events that are qualified for fusion devices.

3.3.3. Liquid surface development

Research Need	Work Description	Expected Outcome
Liquid surfaces have been considered as alternatives for solid surface PFCs but there are very few tests of liquid surfaces on fusion devices and the results are not always positive	Conduct liquid surface flow and heat removal experiments in the laboratory to develop a database for creation and verification of MHD models suitable for extrapolation to fusion devices	Fully qualified liquid surface PFCs for fusion machines.

3.3.4. Innovative divertor magnetic configurations

Research Need	Work Description	Expected Outcome
Most fusion devices have either single or double null divertor configurations that have limitations on the ability for control of heat and particle flux to the PFCs. Innovative magnetic configurations might break the constraints	Advance the modeling of innovative magnetic configurations such as super-X or snowflake to the point where they can be tested on fusion devices. Use those tests to determine the heat flux reduction and erosion control capabilities and off-normal event characteristics.	Divertor and PFC configurations having increased core plasma power capabilities with increased off-normal event margin.

3.3.5. High power density RF components

Research Need	Work Description	Expected Outcome
RF launcher and antenna power capability is limited by the capability of the plasma facing parts of the components	Develop specific materials, coatings, and heat sinks suitable for high power RF components in fusion environment	Higher power density RF components that are robust and tolerant of plasma conditions.

3.4. Enabling the next generation of fusion devices.

Will the components and models developed in thrusts 1-3 produce PFCs that meet the needs of long-pulse high-power non-nuclear fusion devices?

After completion of the development activities in thrusts 1-3, components must be designed for a working fusion device. The operation of that device will provide the proof of the validity of the modeling and laboratory qualification tests. It is time to break the model that each device does their own development and design for a new machine. A coordinated effort on thrusts 1-3 will have a greater chance of delivering qualified components to any new machine. The operation of the machine will validate the predictions of plasma edge conditions, heat flux margins, and robustness for off-normal events. The characteristics of the device should be …

3.4.1. Integrated modeling test

Research Need	Work Description	Expected Outcome
Integrated test of advanced SOL and Divertor models, PWI/PMI models, accumulated run time without large off-normal events, He control and pumping	SOL parameters will be predicted before the device operates and checked against observations. Erosion can be measured and compared to models since the plasma operating time will be long.	Final validation of the theory and models for SOL, erosion, surface modification, RF sheath effects, etc.

3.4.2. Integrated PFC test

Research Need	Work Description	Expected Outcome
Integrated PFC test	PFCs will be subjected to long pulses (thermal creep) and many cyclic loads (thermal fatigue) and off normal events (robustness)	Qualified components for a fusion nuclear device.

3.4.3. Integrated diagnostics and internal components test

Research Need	Work Description	Expected Outcome
Integrated testing of diagnostics, RF and microwave components, and internal coils	Demonstration of diagnostics that will give accurate data under severe conditions, Operation of RF components at high power density under varying plasma conditions, Operation of internal coils that are robust and control off-normal events	Qualified components for a fusion nuclear device.

3.5. Provision of reliable robust plasma edge configurations and plasma facing components for a long-pulse, high-power, fusion nuclear machine

Can the combination of materials development, innovative plasma edge configurations, improved edge diagnostics, first principles models, and innovative components provide solutions for a fusion nuclear device?

3.6. Understanding the Impact of and control of off-normal events

How can we lessen the severity of off-normal events or improve the capability of PFCs to absorb off-normal heat loads?

In a high-power-density long-pulse high-fluence fusion device plasma facing components are designed to remove plasma power in steady state. Because of the high heat flux the components have short thermal time constants and little margin for excess heat load. Off-normal heat flux can lead to catastrophic failure of the PFC. It is critical that the core plasma be controlled to lessen the severity of off-normal events (see Theme 1 or 2), but innovative PFCs may be able to improve the capability to absorb off-normal events.

3.6.1. Modeling and analysis

Research Need
3D edge interaction models, core-integration, analysis of mitigation techniques

3.6.2. Avoidance and mitigation

Research Need
Disruption and ELM avoidance and mitigation

3.6.3. Internal coils in a neutron environment.

Research Need
internal coil design and optimization in neutron environment

4. Harnessing Fusion Power

4.1. Fusion Nuclear Science Thrust

What research will enable the scientific advancement and discovery needed to achieve fusion fuel cycle self-sufficiency and to extract fusion power efficiently, safely and with minimal environmental impact?

This thrust includes all the nuclear-related research required to test, discover, and establish the scientific and technical basis for 1) a self-sufficient fusion fuel cycle together with 2) efficient extraction of fusion power in a safe, reliable and environmentally attractive manner.

- For the fuel cycle, research is needed on methods, components and systems to: fuel the fusion plasma with deuterium/tritium (D/T); recover unburned fuel from the plasma exhaust; breed tritium in lithium-bearing blanket materials; extract, process and recycle T to the fueling system; control, contain and store T to assure steady and safe operation for plant personnel and the general public; and account for T throughout the plant.
- For power extraction, research is needed on systems required to assure efficient power recovery from plasma facing components (first walls and divertors) and the tritium breeding blanket, where the majority of the fusion neutron energy is deposited.
- To assure reliable operation and the highest possible availability for future fusion experimental and power-producing facilities, research is required on 1) remote maintenance systems capable of rapid and efficient repair and/or replacement of plasma chamber components in a radiation environment and complex geometry, and 2) robust radiation-hardened diagnostics and instrumentation for real-time monitoring of plasma chamber conditions and inspection of critical components to assure efficient and safe operation.
- Aspects of the above can be tested and demonstrated in ITER (e.g., utilizing the test blanket module (TBM) capabilities, some fueling systems, particular remote maintenance equipment and processes, safety assessment for licensing, etc.) and other experimental fusion facilities (e.g., where reliability data can be collected).
- Ultimately, this thrust includes testing of the above systems in a fully integrated fusion nuclear science facility (FNSF), to discover, verify, and advance the scientific and technical basis needed to begin engineering and technology development for a magnetic fusion Demo.

The sub-elements of this thrust are:

4.1.1. Create, model and test techniques, components, and sub-scale systems needed for efficient (i.e., high temperature), safe (i.e., minimized at-risk energy and materials inventories), and reliable power handling and extraction in non-nuclear experiments and facilities, with an initial focus on the most significant challenges of effectively utilizing high temperature coolants and breeders.

4.1.2. Create, model and test techniques, components, and facilities needed to reliably, efficiently, and safely fuel the fusion plasma, including T recovery from the plasma chamber and breeding materials.

4.1.3. Develop and test remote maintenance approaches, techniques and equipment capable of operating in a fusion nuclear environment while achieving the efficiency of in-vessel maintenance required to meet availability goals. This includes development and integration of the components, remote handling systems and facility designs.

4.1.4. Understand failure modes, their impact on safety assessments, and conduct a reliability improvement program.

4.1.5. Utilize ITER burning plasma to provide an integrated test bed for investigating all elements in 4.1 and 4.2 via test blanket module experiments (i.e., ITER-TBM) with relevant materials, designs and operating temperatures.

4.1.6. Address and resolve key knowledge gaps fusion nuclear science in a fully integrated fusion nuclear science facility (FNSF). Steps include: a) Define research requirements and mission, evaluate alternatives through first stages of design and R&D, and select a FNSF option(s) and; b) Design, build and operate FNSF to close key knowledge gaps in the fusion nuclear science and technology needed for Demo.

4.2. Fusion Materials Science and Engineering Science Thrust.

What research will enable the scientific advancement and discovery needed to have confidence that materials and components can perform safely and reliably in the harsh fusion environment?

This thrust on material and engineering science establishes the feasibility of designing, constructing and operating a fusion energy system with materials and components that can survive the fusion environment and meet objectives for safety, environment and performance. This thrust includes the following:

- Research needed to develop and qualify (to the point of being licensable), materials and engineered components that can operate safely and reliably for a long enough time to achieve high availability and have minimal environmental impact during operation and upon decommissioning of the power plant.
- Fundamental materials science modeling and experiments on existing, evolutionary and revolutionary materials for plasma chamber first walls, divertors, breeding blankets and chamber structures.
- Nuclear and non-nuclear testing to evaluate performance sustaining material properties and the evolution of these properties in prototypical components with neutron radiation damage, including consideration of the effects of the anticipated operating environment (temperature, stress, cyclic loading, etc.). Neutron radiation damage testing in a facility capable of producing a fusion-relevant neutron spectrum is essential.
- The materials science work must be closely coupled with and be responsive to structural design requirements to ensure safe and reliable performance of integrated and complex components. While listed as a separate thrust, the Materials Science and Engineering Science Thrust must be closely coordinated and integrated with the Fusion Nuclear Science Thrust described above and with related elements of the Taming the Plasma-Material Interface Theme.

The sub-elements are:

4.2.1. Develop and experimentally validate multiphysics, multiscale (i.e., spanning many orders of magnitude in time and space) models describing the behavior, failure paths, and lifetimes of materials in the fusion environment.

4.2.2. Pursue approaches to improving the performance of existing and near-term materials, while concurrently developing the next generation of high-performance materials with revolutionary properties, which are essential for attainment of economical, safe and reliable fusion power systems.

4.2.3. Establish and implement an integrated, concurrent materials-structure development, design and testing approach to fusion systems, starting with materials selection and ending with qualification of materials, components and structures. (This element crosscuts all activities in both the Harnessing Fusion Power and Taming the Plasma-Material Interface Themes.)

4.2.4. Develop and experimentally validate material fabrication and joining techniques providing required performance and reliability during operation in the fusion environment.

4.2.5. Utilize specifically designed non-nuclear structural testing facilities and ultimately nuclear testing facilities to reveal fundamental material and component performance limits, and benchmark models of materials behavior.

4.2.6. Establish the underlying science basis for recycling and free-release of fusion materials to minimize need for disposal.

4.2.7. Evaluate options, select and facilitate the experimental tools (e.g., large volume, fusion-relevant neutron sources such as upgraded existing accelerator sources, IFMIF, or the FNSF) needed to explore fusion relevant radiation damage to materials, components and structures.

4.3. Science-Based Modeling and System Integration Thrust.

What modeling tools, validating experiments and integrated design activities will enable the scientific advancement and discovery needed to underpin and guide the research needed to harness fusion power?

This thrust provides cross-cutting modeling and systems design and integration activities to fully understand, improve and advance all aspects related to harnessing fusion power (see 4.1 and 4.2), including:

- Development of a variety of models, with increasing levels of definition and integration, required to guide and interpret research and make design choices that will lead to the most attractive and feasible future fusion experimental and energy systems. Model validation through experiment is a key aspect of this thrust.
- Collecting operating experience information (e.g., system performance, occupational radiation exposure, industrial safety, and reliability data) from existing and near-term experimental facilities to improve the predictive capability of models.
- Conducting a more detailed integrated conceptual design activity to help identify research areas with high leverage and to assure a balance between competing objectives, while meeting physics and engineering constraints and seeking the goals of safe, economical, and environmentally attractive end product. In the near-term, the integrated design activity will focus on DEMO and required fusion R&D facilities to close the gap to DEMO (e.g. the FNSF).

The sub-elements are:

4.3.1. Develop science-based, fully integrated, predictive modeling capability, validated by experiments and data collection, for plasma chamber components and related systems needed for fusion energy. Models will cover basic through synergistic physical phenomena and will be utilized to optimize components and systems, inform R&D priorities, and integrate with plasma models by supplying key first wall and divertor temperature, electromagnetic responses, etc. Modeling, experiments and data collection related to safety (e.g., thermal response, tritium and activation product migration), availability (e.g., component lifetime, reliability, and time to repair) and overall system performance and optimization (integrated power extraction and conversion, tritium production and recovery, plasma performance, materials performance, etc.) are included.

4.3.2. Assess and improve key aspects of fusion energy through advanced design and integration activities for DEMO, laying out scientific basis and guiding research effort to close the gap to DEMO (including design effort on fusion R&D facilities such as FNSF).

5. Optimizing the Magnetic Configuration

5.1. Demonstrate and understand sustained high beta plasma confinement at reduced aspect ratio.

This thrust represents magnetic configuration optimization through reduction of the aspect ratio. Potential advantages are more compact fusion systems with high beta and large self-driven plasma current. Thrust elements 5.1.1-5.1.5 represent the core scientific research needs for the development of the spherical torus. Thrust elements 5.1.6-5.1.7 represent potential advantage of simultaneous reduced aspect ratio and low externally applied magnetic field. While compact torus (spheromak and FRC) configurations seek the ultimate limit in reduced aspect ratio where no physical structure links the plasma torus, their core research needs have been located in Thrust 5.3, since they equally explore low external field.

5.1.1. Develop plasma start-up and ramp-up innovations with low transformer flux
5.1.2. Demonstrate and understand a plasma-material interface at high heat flux, high temperature, and low density
5.1.3. Understand electron and ion confinement in high beta, low collisionality plasmas
5.1.4. Achieve and understand integrated, continuous high beta, low collisionality, broad current profile ST plasmas
5.1.5. Develop normally-conducting radiation-tolerant magnets
5.1.6. Understand confinement and stability in compact tori with beta ≤1 and with vanishingly small poloidal flux outside the separatrix to attain unity aspect ratio
5.1.7. Evaluate RFP stability and confinement with maximum pressure-driven “bootstrap” current at high beta and low aspect ratio.

5.2. Optimize steady-state, disruption-free plasma confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles.

This thrust represents magnetic configuration optimization through the use of 3D magnetic shaping. Potential advantages are steady-state fusion systems that do not require external current drive and that do not exhibit major disruptions. Thrust elements 5.2.1-5.2.7 represent the core scientific research needs for the development of quasi-symmetric stellarator configurations that minimize neoclassical transport. Thrust elements 5.2.8-5.2.10 represent research needs to assess 3D shaping for targeted improvements in a broader range of magnetic configurations, through small to moderate use of non-axisymmetric field components.

5.2.1. Improve the design and construction of 3D coils through a combination of advanced engineering and physics optimization
5.2.2. Demonstrate and understand the advantages of quasi-symmetry to attain high performance in stellarator confinement (e.g., high beta and low collisionality)
5.2.3. Develop predictive capability for toroidal confinement that covers 3D shaping, building on and in collaboration with axisymmetric tokamaks and other magnetic configurations.
5.2.4. Establish advanced divertor designs compatible with quasi-symmetric 3D shaping that can handle the necessary power exhaust and control neutral particle/impurity influx
5.2.5. Identify and understand expanded operational boundaries using 3D shaping to avoid disruptions and other transient events; what is the physics of soft beta limits in stellarators and how much plasma current is permissible while avoiding the Greenwald limit, disruptions, and profile stiffness?
5.2.6. Understand neoclassical and turbulent transport physics for controlling impurity transport and helium expulsion in quasi-symmetric stellarator configurations
5.2.7. Predict and confirm the thresholds for fast ion losses with respect to the breaking of quasi-symmetry as well as through nonlinear kinetic interaction.
5.2.8. Apply varying degree of 3D shaping to a broad range of magnetic configurations to achieve specific benefits from 3D control tools and analysis techniques
5.2.9. Develop innovative approaches to the production of the 3D fields required for optimized stellarator confinement and non-axisymmetric shaping of tokamaks and other magnetic configurations. This element spans the physics basis of efficient and flexible trim coils to the explorations of novel HTS steady-state configurations
5.2.10. Understand improved RFP confinement using 3D shaping, by optimizing spontaneous single-helicity magnetic self-organization, or by application of non-axisymmetric field

5.3. Achieve high performance plasma confinement using minimal externally applied magnetic field.

This thrust represents magnetic configuration optimization by minimizing the strength of the externally applied magnetic field. Potential advantages for fusion are very high engineering beta, with lessened demands on external magnets, and efficient Ohmic heating from large plasma current. Thrust elements 5.3.1-5.3.4 represent the core scientific research needs for the development of the reversed field pinch (RFP). Thrust elements 5.3.5-5.3.8 represent the core scientific research needs for the development of compact tori, i.e., the spheromak and field-reversed configuration (FRC). Thrust element 5.3.9 represents the need for predictive modeling having sufficient scope to cover magnetic configurations with dominant poloidal magnetic field.

5.3.1. Understand transport mechanisms and confinement scaling for inductively sustained RFP plasmas at high Lundquist number, with and without magnetic self-organization
5.3.2. Test and understand steady-state current sustainment using AC magnetic helicity injection and its impact on confinement at high Lundquist number
5.3.3. Establish divertor configurations and other advanced boundary control in axisymmetric plasmas with weak toroidal magnetic field
5.3.4. Demonstrate high performance RFP plasmas, sustained using efficient current drive, with control of the plasma-material interface, and robust active feedback stabilization of resistive wall modes
5.3.5. Study FRC stability for a wide range of the *s* parameter, the ratio of plasma radius to the Larmor radius
5.3.6. Demonstrate spheromak formation and sustainment compatible with good confinement
5.3.7. Understand the integrated impacts of FRC physics in the fusion plasma, high-beta regime using NBI or RF, addressing transport, current drive, fast particles, heating and other important physics
5.3.8. Understand the integrated impacts of spheromak physics in the fusion-plasma regime, including transport, beta limits, and particle balance and density control
5.3.9. Develop modeling capability that will predict the synergy and scaling of macroscopic dynamics and transport when testing current drive and beta limits in low-*q* configurations such as the RFP and spheromak