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Fusion Nuclear Science and Technology R&D Needs

– A fusion nuclear renaissance –

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INTRODUCTION

Fusion is a form of nuclear energy, and many aspects of the feasibility and attractiveness of fusion, in any of its configurations or applications, depend upon nuclear phenomena. Yet progress toward applying fusion to productive ends has been severely impeded in the US following decades of neglect and decay in fusion nuclear science and technology (FNST) research. Advocates from the scientific community regularly appeal for a balanced program, but fusion nuclear research has continued its decline due to a combination of political, technical and financial factors. In the era of ITER, with increasing attention to the necessary steps beyond ITER, the US is faced with the unpleasant reality that our leadership role has been lost, and our ability to contribute to the ITER energy mission and to exploit its capabilities are in serious doubt.

This has not always been the case. During the 1980's and early 90's, the US led the international community in FNST research. Healthy programs at the DOE laboratories, including Argonne, Oak Ridge, Los Alamos, Sandia and Idaho, were complemented by vibrant and well-funded university programs at institutions such as MIT, the University of California and the University of Wisconsin. US researchers trained international collaborators, hosted them at our facilities, and were instrumental in the initiation of international collaborations and symposia.

The US cannot continue to postpone attention to this research subject if it is serious about pursuing a "DEMO in the 2035-2040 time frame". Moreover, the characteristics of and pathway toward a Demo, or toward any other concept of a fusion application, cannot be meaningfully defined in the absence of FNST research.

The US needs a comprehensive rethinking of its program priorities and the structure of its FNST activities. The FNST workforce has been depleted after decades of attrition, retirements and discouragement of the younger generation. Considering the current state of affairs, we believe that a rebuilding effort should be started immediately. This rebuilding requires broader opportunities for university participation, a stronger advocacy role played by one or more DOE laboratories, and mechanisms for industry to become involved in manufacturing and development aspects of fusion nuclear components.

In order for the fusion energy sciences program to impact our energy future and contribute to "American competitiveness", there must be a balanced consideration of the economic and viability concerns that originate from nuclear science and technology disciplines. We must identify unique opportunities for American leadership and create a coordinated, focused program to pursue these opportunities. This document describes several of the fundamental challenges involving fusion nuclear science and technology, provides examples of near-term, high-impact R&D that could be initiated, and proposes a new vision for fusion nuclear R&D that can be implemented with modest levels of support.

SCIENTIFIC AND TECHNICAL CHALLENGES

The practicality of fusion as an energy source depends on many complex nuclear issues, involving both in-vessel and ex-vessel components and systems. The issues can be lumped into just a few fundamental questions that can be considered the "grand challenges" for fusion nuclear science and technology. These include:

- Power management
- Tritium management
- Plant operations
- Long-term materials survival and performance

These challenges are briefly described below, together with examples of important R&D that could be performed in the near term.

Power management

Power management is a core issue for an attractive fusion energy source. It involves the ability to produce power, control its release, maintain components within their operating limits, extract the energy efficiently and convert it to a useful end product. The primary source of power from fusion is the burning plasma, which produces energetic neutrons, charged particles, and radiation that in turn generate a significant amount of additional energy in the first wall and blanket due to nuclear reactions. Because of the central role played by the plasma, resolving the issue of power management inherently requires a tight coupling of plasma and component engineering.

The characteristics of energy production and utilization in fusion are significantly different than other, more "conventional" energy sources, including fission reactors. Examples of these unique attributes include:

- Very high surface heat loads and potentially high peaking factors, combined with damage caused by energetic particles and neutrons,
- Heat transfer that can be strongly affected by magnetic fields and by neutron-induced changes in materials,
- Temperature and stress control requirements in components, due in large part to compatibility of unique combinations of materials and due to changes in materials behavior in a 14-MeV neutron environment.

Many fundamental uncertainties remain in our ability to control power flows and to accommodate them in the surrounding structures with acceptable reliability and lifetime. In some cases, we still do not have adequate understanding of fundamental behaviors, such as materials compatibility at high temperature or liquid metal fluid flow in a strong magnetic field.

In order to address the challenge of energy extraction and utilization in fusion, R&D is required in both neutron and non-neutron environments. Power management is an excellent example of an issue that can benefit from expanded utilization of relatively inexpensive non-neutron facilities. For example, the control of power flows in the plasma and interactions between these power flows and the surrounding plasma-facing components can be addressed in plasma confinement devices and simulation facilities, such as e-beam and PMI facilities. Fluid flow, materials compatibility and structural response experiments can be performed in small-scale "benchtop" type facilities.

Tritium management

Fuel for mankind's initial endeavor into fusion power must include tritium, a radioactive isotope of the most abundant element in the universe, yet found nowhere in nature. Fortunately, tritium can be produced by neutron reactions with other naturally occurring elements, such as lithium, and the fuel can be generated in a self-sufficient fashion at a fusion power plant. Efficient tritium management becomes crucial for safe, clean, and economical operation of the fusion power plant – a grand challenge because tritium's radioactivity and its ability as a hydrogen isotope to pass through a variety of materials frustrate efforts at inventory control.

Many issues regarding tritium storage, core delivery, exhaust processing, and isotope separation will be perfected in ITER at a scale relevant to Demo and future fusion power plants. ITER will not, however, utilize systems capable of breeding and handling tritium in sufficient quantities to explore the issues of tritium management in Demo. A few promising breeder concepts may be tested on a small scale in ITER's multiple-effects fusion environment, including 14 MeV neutrons, magnetic fields, thermal loadings and cycling, and maintenance process. From this important first step at a much-reduced scale, essential missing ingredients for a full blanket system deployed in Demo include:

- Control of the tritium breeding rate,
- Suitable tritium extraction rates from the various coolants,
- Increased inventory of activation (corrosion) products,
- Control of permeation into surrounding structures at high tritium breeding rates,
- Impact on in-vessel tritium inventory in plasma-facing components and dust/debris.

Advancement on many of these issues requires a focused R&D effort into the underlying processes at work in the materials. For instance, efficient tritium extraction from breeding materials and coolants requires detailed knowledge of tritium solubility and permeability, as well as the changes in such parameters during high energy neutron irradiation. The principal challenge lies in taking the knowledge gained at the fundamental level and developing systems that suitably perform when applied at the scale relevant for Demo. One approach to allow testing of scalability involves one or more development facilities on the path to Demo, such as the concept of the "CTF." Given public sensitivity in the modern era to tritium environmental release, safe and reliable implementation of a tritium management scheme on the scale needed for a fusion power plant must be achieved if fusion power is to be successful.

Since there is no practical external source of tritium for fusion energy development beyond ITER, all subsequent fusion systems must breed their own tritium. Ensuring tritium self-sufficiency in future fusion systems is a prerequisite for the development of DT fusion. It is important to accurately predict and control the tritium breeding ratio, both to avoid deficiency in tritium fuel supply and to avoid generating excess tritium (for safety concerns). To reduce uncertainties in predicting tritium breeding, R&D programs are needed in the area of accurate geometry modeling for nuclear analysis using CAD models. In addition, we need to utilize DT accelerator based 14 MeV neutron source facilities to carry out integral experiments on mock-ups for the US preferred blanket concepts.

Operations

The fusion experiments of today occur in complex, highly sophisticated devices that require a cadre of physicists and engineers to operate. A power plant, including a Demo, must be operable by a modest staff of operators and require minimal human intervention. The plant must operate with high reliability and the ability to perform routine and unplanned maintenance quickly, in a highly radioactive environment. Tokamak experimental programs around the world, including ITER, are providing a growing base of operating experience, but the required level of reliability, maintainability and operability of a power plant is far beyond the current state of the art.

Operations involve plasma, component and system-level concerns. For example, the operating space of tokamak plasmas must be mapped out and disruption-free operating points demonstrated with a high degree of confidence. Instrumentation and control of these plasmas are also essential, including the ability to actively control power levels and power flows, and to react quickly to off-normal conditions so that power production can continue or a soft shutdown can be implemented.

Component-level issues include similar concerns over reliability, instrumentation and control. Nuclear components are especially vulnerable due to the high temperatures, stresses, particle fluxes and intense high-energy neutron environment. Research must be performed to identify failure modes and rates, develop innovative design concepts to reduce uncertainties, and obtain data to verify acceptable performance and lifetime. As with all fusion nuclear issues, a sequence of single-effects and integrated experiments combined with an expanded program of numerical simulation is needed.

System-wide issues include systems interfaces and plant maintenance. Power and tritium management are also good examples of the importance of a system-wide approach, as they cross boundaries between many components and systems.

Long-term materials survival and performance

All of the critical issues for fusion energy depend in one way or another on materials performance, which is factored into any one of the grand challenges. However, the uniqueness of the fusion DT neutron source and operating environment elevate materials survival to the level of a grand challenge. Indeed, a large fraction of the funding in FNST historically has been allocated to neutron damage effects, though this funding has decreased dramatically over the last several years.

A lifetime of the order of 1-2 years for in-vessel components is considered an absolute minimum in order to meet availability goals for power plants. At present, the survival of candidate materials cannot be assured for this length of time, primarily due to uncertainties in property changes caused by neutron irradiation in a realistic fusion environment. Issues to be addressed comprise both outright failure (including the effect of fracture and plastic instabilities), as well as performance reductions caused by properties changes. For example, thermal conductivity, tritium solubility, and many other parameters can be degraded by neutrons to push components or systems outside their design window. One promising approach to elucidate properties degradation and allow assessment of possible solutions applies the rapidly advancing multi-scale modeling methods being developed for a host of materials concerns in fusion, fission, and elsewhere.

The R&D effort requires a combined experimental and theory approach to address the effects of radiation damage in metals and ceramics envisioned for use in a DEMO. The need for neutron sources and hot cells for sample characterization and testing motivates a strong collaborative relationship between universities and the national laboratories that traditionally provide irradiation facilities and expertise in post-irradiation examination. Involvement of university programs is imperative because these programs most often advance the technical foundation for understanding and predicting irradiated materials behavior, in addition to training the future generations of fusion energy researchers.

The issue of 14-MeV neutron irradiation of materials has a long and complex history, and involves significant international ramifications. In the near term, the most productive R&D opportunities for the US include modeling and fission reactor testing.

THE NEED FOR A "FUSION NUCLEAR RENAISSANCE"

A demonstration power plant is a facility that integrates all of the science and technology needed for an attractive, commercially-competitive fusion energy source. While the Demo itself may be allowed to generate electricity at a somewhat higher cost and lower availability, it must contain all of the essential elements of a competitive power plant. Due to the high cost of a Demo, the requirement for nuclear regulatory approval, and the timescale involved in its design, construction and operation, the risk of failure must be very low. The R&D program prior to Demo **must** provide a high degree of confidence in the operation of its nuclear components and systems.

ITER alone is not adequate to develop and demonstrate technologies for a Demo. Few people believe that the parameters, plasma performance and nuclear systems in ITER are sufficient to demonstrate reactor-relevant physics and technology. A combination of fusion facilities such as the "CTF" defined by FESAC and non-fusion facilities, including neutron sources, fission reactor irradiations and non-neutron experiments, are needed to fill the gap. But facilities alone cannot solve the remaining issues for attractive fusion energy systems. The expertise to construct these facilities, productively exploit the data obtained and perform complex numerical simulations will require a competent and highly skilled workforce.

Unfortunately, the US fusion nuclear program has been severely depleted. Our readiness to proceed on a path to Demo will require significant rebuilding of capabilities and competencies. The time scale for this kind of rebuilding is measured in *decades*, and not *years*. This time scale is dictated not only by the need for extensive model development and simulation activities, and the design, construction and operation of experimental facilities, but also by the need to educate and train a completely new generation of researchers qualified to invent a new source of energy. The US workforce is severely underpopulated, having suffered literally decades of neglect in hiring and the steady loss of intellectual leadership by retirement and attrition.

We cannot afford to wait any longer to initiate these changes if we are serious about a Demo in the 2035-2040 time frame. “Business as usual” will certainly lead to our inability to proceed with a Demo due to a lack of credible fusion nuclear technologies. Already our ability to participate in ITER and extract value from its nuclear test program is being seriously questioned.

Our vision of restructuring is anchored by the desire to establish a US leadership role in the international community. We should attempt to maintain close collaborations with our international partners in ITER and Demo R&D, but a top priority should be placed on asserting our “American competitiveness” in at least one unique area of fusion nuclear research.

We believe that concept innovation and improvement offers a unique opportunity for the US FNST program. The US has historically played this role, both in plasma physics and fusion technology, by pushing the international community toward a more attractive end product. Concept innovation and improvement can be achieved with relatively modest funding levels and should utilize the unique attributes of university programs, national laboratories, and industrial partners. Universities are well positioned to exploit the latest developments in science and technology for the benefit of fusion. National laboratories can play the important role of coordinating, focusing and partnering in the research, and are needed to champion fusion nuclear technology within the DOE framework. Industry plays an essential role not only in the long-term development of fusion, but also in providing advanced technology for near-term experiments. A rational, coordinated and focused program involving all of these players is required in order to succeed in the development of fusion energy.

This program of concept innovation and improvement can begin immediately. There are numerous examples of low-cost, near-term R&D tasks that are possible under all four grand challenge topics listed above; it is beyond the scope of this white paper to itemize them all in detail. More detailed information is currently being collected and updated as part of the ARIES Pathways Study.

We urge FESAC to support restructuring of fusion nuclear science and technology and recommend adequate resources to initiate the transition to a coordinated R&D program to enable the US to proceed toward an attractive and credible fusion demonstration reactor.