A US ITER Research Team for Full Participation in and Benefit From ITER

US Burning Plasma Organization
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INTRODUCTION

Recent strategic planning activities by the US Fusion community[1], the Fusion Energy Sciences Advisory Committee (FESAC)[2], and the National Academies of Sciences, Engineering, and Medicine[3,4] laid out an ambitious plan to move toward rapid deployment of a Fusion Pilot Plant (FPP) in the United States. This will require a major evolution of the US Fusion Energy Sciences program to complete the needed scientific and technological basis in time to bring this plan to fruition.

An important piece of this strategy, as articulated by the NASEM report, is the successful construction, assembly, commissioning, and research operation of the ITER tokamak facility, now under construction in the South of France, by seven international members including the US. The report notes that even with an accelerated timeline for a US FPP, the ITER project will yield invaluable scientific and technical information on reactor scale plasmas and systems integration required to establish the design basis for FPP. Although responsible for only a small fraction of ITER's costs, the US is entitled to all of the intellectual property generated by this endeavor. As described in Ref. 4, this intellectual property is needed and assumed as part of the path to fusion electricity. This is a promising element for a fast track to an US FPP.

In order to secure the full benefit of ITER participation, the United States Burning Plasma Organization (USBPO) recommends the immediate formation of a community-led US ITER Research Team (USIRT). Forming the USIRT now will help ensure timely access to ITER's full value, in terms of both experience and intellectual property. It also will provide a fast-track pathway to build the workforce for the burning plasma science and engineering domain needed to construct and operate an FPP.

ITER represents major advances in both the science and technology of fusion, and so both of these segments of the US fusion community should participate in the USIRT. The team described here is US-specific, but all participants should be considered part of the international ITER Team, party to and with rights from the ITER implementing agreement[5], and able to join ITER Task Forces and participate in proposal writing and analysis. Since US interests in ITER may be broader than the highest priority objectives of the ITER Research Plan[6] (IRP), the USIRT will be charged to advocate for research in areas that may be needed for the US vision of an FPP (e.g. steady-state scenarios).

A 2015 report from a USBPO committee[7] made recommendations on US team formation and participation in ITER. We continue to endorse the conclusions of this report. Recently updated estimates[8] of the size and makeup of the USIRT suggest a need for 150-180 FTEs, including 50-60 scientists, 50-60 technicians and engineers, and 50-60 additional staff needed to fulfill US commitments to ITER Operations. We anticipate a gradual ramp-up of staffing, starting immediately with a focused group of people spending part of their time on ITER-specific activities. Full staffing will be reached during successive research phases of the ITER program. In addition to the work directly supporting the ITER Organization (IO), significant investment is needed to develop the computational capabilities to enable broad US scientific engagement in ITER. As the report notes, there will be a need for infrastructure in the US to support remote participation, during planning, execution, and analysis of ITER experiments. Since there has been considerable progress in the development of tools for remote participation, and since the ITER data structure has been defined, there is an urgent need to identify the best interfaces and build solutions for optimized US participation in coordination with the IO.

WHY ITER?

ITER will provide the US with the knowledge and experience that comes from operating a first-of-a-kind power-plant scale burning plasma facility. It is already paying dividends in the technology arena as the plant is under construction and tokamak assembly is underway. When it begins non-nuclear research operation in 2028 it will provide our first opportunity to carry out scientific studies of reactor-grade plasmas. When it operates with a deuterium-tritium mix in 2035 it will provide our community's first access to a self-heated (fusion gain $Q \approx 10$, alpha heating fraction $P_{\alpha}/P_{heat} \approx 2/3$) reactor-grade plasma. As an *experiment*, ITER will offer opportunities to gain understanding of the behavior of and optimize the performance and control of such a plasma. During the fusion power phase of the IRP the plant will rely on new technologies including a first-of-a-kind tritium processing facility. These new technologies will also be vital for the US FPP.

The importance of US participation in ITER[1,2,3,4,7,9] is well documented and has been endorsed by the US Fusion community, most recently in the DPP Community Planning Process (CPP)[1] and FESAC Long-range Planning (LRP)[2] reports as well as the 2018 Burning Plasma Report of the National Academy of Sciences[3]. The US is already heavily invested in the ITER construction project, with responsibility for major systems including key diagnostics and substantial cash and in-kind contributions already made and in progress. US investment into ITER is the single largest capital investment the DOE Office of Science has ever undertaken. At this time, however, the allocation of resources does not allow the US fusion program to take full advantage of this investment. The proposed formation of the USIRT presented herein is the first logical step to overcome this gap and take full advantage from ITER.

Construction and full operation of a FPP and subsequent first-of-a-kind power plant will rely upon the knowledge and experience gained from ITER's success. Results from commissioning and operation of ITER will be important throughout the life cycle of an FPP, and the demonstration and optimization of fusion burn in ITER can contribute greatly to the operation of even a fast-tracked FPP.

THE US ITER RESEARCH TEAM

The CPP[1] and FESAC LRP[2] reports included among their recommendations, a program to develop the US workforce for domestic and onsite ITER participation:

> *The ITER international experiment is the largest single investment by DOE FES, and a US ITER research team needs to be formed to leverage it. That team will make essential contributions to achieving the high gain mission for ITER, exploit unique access to a burning plasma at the reactor scale, and enable US scientists to close the nuclear science and engineering gaps in order to build an FPP. [Ref. 2, page 13]*

The proposed fusion long-range plan includes a call for US participation in all phases of the ITER program, including integrated commissioning, tokamak operations and research, and eventually safe decommissioning. Key areas for US participation also include nuclear engineering and technology aspects of ITER, that need to be harvested and fully leveraged to prepare for FPP design, construction, and operation.

ITER presents unique opportunities for scientific and engineering workforce development for the US and provides exciting opportunities for career growth in science and engineering. One of the important products of the ITER Research Program will be the development of the workforce that is required for a US fusion power plant. The USIRT should work with the IO to create opportunities for US researchers and engineers on ITER, similar to what the other ITER partners are currently doing through a variety of programs.

The formation of a USIRT will provide an organizing point for US engineers and scientists to participate in ITER research and operations, and to provide a mechanism where the US can leverage ITER to meet US workforce needs for FPP design, construction and operation. The USIRT should grow from the US research and technology community; the US ITER Project Office (USIPO) is responsible for providing US hardware for the construction of ITER, including some of the diagnostic systems, but is not responsible for developing the ITER research and operations workforce. The USIPO role will continue at least through the completion of the ITER plant in the mid-2030s, but the USIRT will need to incorporate members of the research community, both science and technology. The team should ultimately integrate scientists, engineers, diagnosticians, computer experts, etc.… all of the specialties that will make ITER succeed and bring home knowledge and experience to move to next steps.

What does the team do and when does it need to do it?

The current ITER schedule (Figure 1) includes first plasma at the end of 2025, a little less than five years from now. Prior to first plasma we will need to have "boots on the ground," for various purposes including commissioning and operations (engineering and technology), science (ITER research planning) and support (analysis and remote participation infrastructure for US engagement in ITER operations). This presence will need to grow for the subsequent research campaigns that will take place beginning in 2028, 2032, 2035, and beyond.

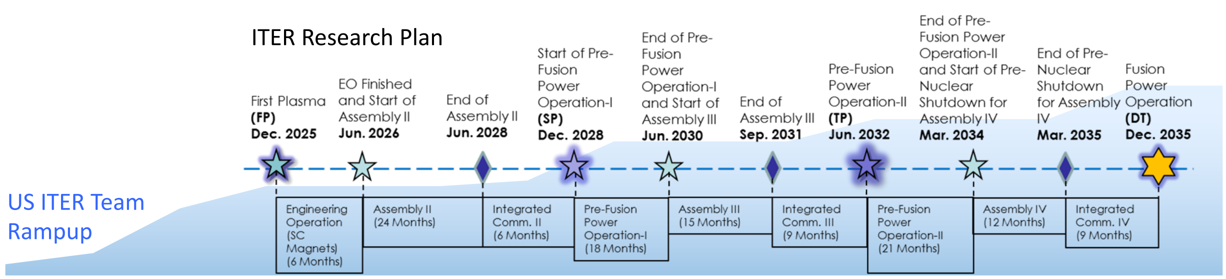

Figure 1. ITER is on track for first plasma in 2025 and a full research program leading to Fusion Power Operation starting in 2035.The US ITER Team should start organizing now and ramp up (blue shading) along with ITER.*

Organization of the USIRT should begin immediately and it should grow and continue throughout ITER's operational lifetime. USIRT priorities should address the IRP needs while providing the necessary knowledge and expertise for the US to accelerate the path to a cost-effective US FPP. We believe that this is best carried out through a single entity drawn from the community and working in concert with DOE.

* Detailed estimates of staffing needs and timetable have not been made; the blue shading is shown as a rough indication of how a ramp-up would play out.

Although detailed staffing estimates have not been undertaken, a rough timeline could be as follows. As we progress through the different stages of the facility and research plans, it will always be important for the US to commit resources to ensure that we gain valuable experience from the integration and commissioning of all aspects of the ITER plant that can contribute to the future of the US burning plasma program.

Immediate	Organize a small core group as a seed for the larger effort. This group would work with FES, the community, the ITER Organization and other ITER members to develop and prioritize US activities and staffing requirements. Enhance ITER science fellowships, Project Associate, and other directly funded early career opportunities to build a workforce platform for the future. Preparation of US domestic infrastructure for remote participation in ITER experiments should begin immediately.
Early 2025	Engineers, technologists, and diagnosticians work on-site at ITER to participate in its commissioning activities (there may be opportunities to start earlier but would require long-term secondments for compliance with the nuclear regulator). Domestic efforts to support ITER operation by state-of-the-art science in modeling and computational engineering support preparations for commissioning and operations.
Late 2025	Members participate from both on- and off-site during First Plasma operations based on US assessment of first plasma participation needs.
Mid 2026	Assembly Phase-II: In the US and onsite at ITER, capabilities for handling and analyzing ITER data should be ramping up using data from the First Plasma phase. Scientists are preparing for the first Pre-Fusion Power Operation Phase (PFPO-1), including modeling and computational engineering efforts.
Mid 2028	US engineers, technologists, and diagnosticians on-site at ITER for commissioning. US scientists and technologists engaged in experimental planning using the full complement of modeling and domestic experimental capabilities required for the design of ITER experiments.
Late 2028	Full complement of US researchers engages both on- and off-site in the first Pre-Fusion Power Operation research phase (PFPO-1). Engineers, technologists and support staff continue to work on-site contributing to operations and supporting US on- and off-site staff.
Mid 2030	ITER Assembly Phase III: Scientists are analyzing data from PFPO-I and preparing for PFPO-II.
Late 2031	Engineers, technologists, and diagnosticians on-site for commissioning.
Mid 2032	Full complement of US researchers engages both on- and off-site in PFPO-II. Opportunities for participation may expand along with ITER's capabilities and the USIRT may be somewhat larger than in PFPO-I. Engineers, technologists and support staff continue to work on-site contributing to operations and researcher analysis needs.
Mid 2034	ITER Assembly Phase IV (pre-nuclear shutdown): In the US, scientists are analyzing data from both PFPO phases and preparing to participate in DT experiments.
Mid 2035	Engineers, technologists, and diagnosticians on-site for ITER commissioning. A critical phase as much of the nuclear technology is commissioned.

Late 2035	DD and DT operation commences with the beginning of Fusion Power Operations 1 (FPO-1). The US Team is now at its full complement, with ITER crossing the line into high-gain fusion power experiments and exploitation of nuclear technology… both first of a kind in fusion. *This level of participation should continue through the entire ITER research program.*
Late 2040s(?)	US engineers and technologists participate in ITER decommissioning. US scientists should have a considerable archive of data to continue analyzing.

As previously mentioned, the above is in addition to ongoing US in-kind and cash contributions made via the USIPO; those activities should continue well into the 2030s. Throughout the above program, USIRT members should emphasize developing the expertise and bringing back all of the intellectual property we are entitled to and need in order to move on to a successful FPP and a US FPP. The USIRT should also be tasked to promote the interests of the US fusion community within the broader group of ITER Members.

The need to initiate the USIRT is urgent in that construction of the ITER facility's infrastructure is already at an advanced stage with tokamak assembly in progress. We can already be learning from the design, procurement, assembly and commissioning of the many ITER components and sub-systems as we begin to think about the FPP. We should already be engaged with the IO in preparing the analysis infrastructure required for effective US participation in ITER. During the ramp-up of the USIRT and the completion of ITER construction, there are many opportunities for US participation, including (note that many of these activities are already underway):

- Provide information and advocacy within the US community
- Recruit researchers to prepare for ITER operation. These researchers would become part-time or full-time ITER Research Team members who would
    - Continue to carry out research on existing facilities (DIII-D, NSTX-U, international collaborations) focusing on addressing ITER research needs[10] and team building. The US community has already established this as an area of strength. The IO has provided a list of areas where such R&D is still needed in reference 10.
    - Develop and familiarize the team with ITER-specific tools for remote participation
    - Engage directly with the IO in form of ITER science fellowships, project associateships or other IO sponsored or endorsed involvement mechanisms.
    - The growing team should develop competence to form dedicated implementing agreements with the IO to become paid contributors to the IO specific research priorities
- Engage in activities aimed at interfacing US facilities and codes with the IMAS (ITER Modeling and Analysis Suite) framework, which has been developed to serve ITER data and modeling. This should build on the IMEG process for coordinating the development of these capabilities.
- Contribute to development of the ITER pulse design and analysis framework. ITER operations will require a high level of pre-experimental pulse design that has not been required or achieved on US or international facilities thus far. To support the pulse-design of ITER discharges, the US should adapt its existing pulse-simulation workflows to the ITER data model and validate them against existing devices.
- Contribute, where possible, to the preparation of ITER's plasma and plant control systems, and develop expertise in using these systems in preparation for US participation in all phases of ITER operation.

- Provide access to seed initiatives and start engagements through ITER Science Fellow Programs, ITER Project Associates, the ITER Operations Network, and new US-specific programs that need to be developed and funded, e.g. a young scientist secondment program. Throughout the entire ITER program, the USIRT should continue to support opportunities for early career scientists, engineers, and technologists to participate and take on meaningful roles.
- Advocate with the ITER Organization and the other Members for addressing US interests in carrying out the IRP
- Where opportunities present, contribute to design and testing of ITER prototype systems (plasma control, disruption mitigation,…) that may not yet be mature
- Where opportunities present, engineers and technologists participate on-site at ITER in facility commissioning. We note that opportunities may be restricted by the French nuclear regulator and would likely require long-term secondment or employment by the IO.

Other considerations

Exactly how USIRT members will participate in ITER has yet to be determined. The USBPO has produced a set of "Recommendations for ITER Experimental Operation, US Team Formation and Participation."[7] Modes of participation will have to be negotiated with the IO and the other ITER Members as an overall research structure is assembled; presumably this will happen at the ITER Council level with DOE representing the USIRT.

As ITER operation begins and progresses it can be anticipated that USIRT members will have opportunities to participate both remotely and on-site at ITER and participate at all levels within the full international ITER Team including leadership positions and access to opportunities for high visibility presentations and publications.

Funding mechanisms will have to take into account the costs of long-term on-site assignments and significant travel. Significant resources will also be needed for off-site participation, perhaps including one or more remote participation facilities and capabilities to handle, store, and analyze large quantities of data.

The needs of personnel at all career levels and institutions must be considered – from students to tenure track faculty in academia, as well as scientists and technicians in laboratories and industry. Training and involvement of these individuals will benefit from strong national coordination focusing on US long-term staffing needs.

Engineering and technology considerations

Modes of US participation in plant operations must be coordinated with the IO in order to maintain compliance with the French regulator and ensure helpful and productive engagement.

The USIRT should be tasked to access the knowledge of all ITER systems (radiation hardened electronics, diagnostics, magnets, cryoplant, vacuum pumps, tritium systems, etc.). Much of this is in place now and will continue to arrive through 2025 and in subsequent upgrade steps up to 2035. Some activity is needed to access this information. The US only provides a small portion of the engineering and technology to ITER, but as a full Member we are entitled to the rest. There is a particular need to involve nuclear licensing and technology specialists, areas where the US fusion community currently has very minimal experience.

The ITER Test Blanket Systems are an exception to the availability of intellectual property to all members. These systems are proprietary, and the US is not currently a participant in that line of research. The USIRT should seek opportunities to collaborate and gain access to data from the Members who own them.

Evolving roles and activities

Several activities that have already been underway within the US community could be rolled into a nascent USIRT, including

- Participation in the International Tokamak Physics Activity (ITPA)
- The USBPO role in evaluating and recommending ITER research needs, assisting DOE in identifying US participants for ITER activities, and providing a communication channel between the IO and US fusion community.
- Advise and support of the IO via participation on committees including the Science and Technology Advisory Committee (STAC), Integrated Modeling Expert Group (IMEG), ITER Research Plan development, design reviews, etc.
- Members of the community work directly with the IO on design reviews and planning and execution of targeted experiments at US facilities
- Entry points into ITER are already being accessed via ITER Science Fellowships, the ITER Operations Network, and the ITER Project Associates program. Expanded participation in these programs is an attractive and immediate step to grow US leadership talent.

Infrastructure needs

As much of the USIRT's work would be done remotely from the US, extensive capabilities for moving, processing, and storing large quantities of data will be needed. One or more remote control rooms, connected to the ITER facility via high-speed networking, would greatly improve the experience and effectiveness of working remotely on ITER. Both international collaboration and recent experience with remote tools during the COVID-19 pandemic[11] have provided a great deal of expertise, as well as having spurred the development of new tools. A worthy goal would be one or more remote facilities and data centers in the United States that mimic as closely as possible the experience of being in the ITER Control Room during experiments.

GOVERNANCE OF THE US ITER RESEARCH TEAM

We recommend formation of a community-based US ITER Research Team. Everybody in the US fusion community can consider themselves a part of "the Team." This levels the playing field, with no single institution having an elevated position, and affirms an "all hands on board" attitude toward ITER. This desire was made very clear during the recent APS-DPP Community Planning Process. Leadership positions within the USIRT should be open to the entire community and should be circulated over time to foster broad representation. The role of the USIRT would be to provide an entry point for broad participation and ensure that US-specific milestones are achieved and made available as part of a roadmap to an FPP.

The USIRT could be built from the ground up, but we propose that the current USBPO should serve as a seed organization. The mission of the USBPO is to "*advance the scientific understanding of burning plasmas and ensure the greatest benefit from a burning plasma experiment by coordinating relevant US fusion research with broad community participation*." This mission aligns well with a potential USIRT, indeed, to date the USBPO has largely focused on ITER as it is the only funded burning plasma research program within the US portfolio. We recognize that given recent developments, new portfolio elements such as SPARC, ARC, and an FPP could fall within the scope of the USBPO as it is currently constituted. This will need to be considered in any reorganization. That having been said, we believe that focusing the USBPO on ITER, the US fusion program's largest investment, is appropriate and necessary at this time. Since ITER research has an equally important engineering/technology component, the Virtual Laboratory for Technology (VLT) should have a partnership role in the formation of the USIRT.

Organization of the USIRT could be decoupled from the funding mechanisms, which are outside the scope of this white paper.

SUMMARY

The recent APS-DPP Community Planning Process brought forward a broad consensus in the US fusion community that it is time to begin formation of a US ITER Research Team. This was reiterated in the report of the FESAC Subcommittee on a Long-Range Strategic Plan for the FES Program. Such a Team will provide an entry point for broad participation of the US fusion science, engineering, and technology communities, and work to ensure that the knowledge gained from ITER can be made available in support of operating a Fusion Pilot Plant in the foreseeable future. The US must begin immediate to form the USIRT in order to prepare for ITER operation and to derive the greatest possible benefit from the construction, commissioning, and operation of ITER, the world's most ambitious scientific and engineering achievement for exploring the science of burning plasmas. With a community-led US research team and adequate resources to accelerate US preparations for ITER operation, we can deliver on the promise of ITER for accelerating the development of fusion energy at home and abroad.

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