# Mission Need Statement

**for the**

**National Spherical Torus eXperiment (NSTX)**

**Upgrade Project**

**Non-Major System Project**

**February 23, 2009**

**Office of Fusion Energy Sciences (OFES)**

**Dr. Patricia Dehmer**

**Approved** Patricia M. Dehmer ____________________

## Statement of Mission Need

An improved understanding of the Spherical Torus (ST) magnetic confinement configuration is needed to establish the physics basis for next-step ST facilities, broaden the scientific understanding of plasma confinement for ITER, and maintain U.S. world leadership in ST research capabilities. In particular, operation at higher magnetic field with reduced plasma collisionality is needed to extend the plasma physics understanding of the ST toward next-step ST facilities and ITER. Controllable fully-non-inductive current-drive will also contribute to assessing the ST as a potentially cost-effective path to fusion energy.

### Alignment

*Program Mission*

DOE's strategic plan calls out two goals:

> **GOAL 3.1 SCIENTIFIC BREAKTHROUGHS**
> Achieve the major scientific discoveries that will drive U.S. competitiveness; inspire America; and revolutionize approaches to the Nation's energy, national security, and environmental quality challenges.
>
> **GOAL 3.2 FOUNDATIONS OF SCIENCE**
> Deliver the scientific facilities, train the next generation of scientists and engineers, and provide the laboratory capabilities and infrastructure required for U.S. scientific primacy.

Finding revolutionary solutions to the national energy challenge and maintaining U.S. leadership in fusion/plasma science requires the best tools - including updated and modern machines and devices. The mission of the U.S. Fusion Energy Sciences (FES) Program is to advance plasma science, fusion science, and fusion technology - the knowledge base needed for an economically and environmentally attractive fusion energy source. Consistent with this mission, the ST configuration for magnetic confinement of fusion plasmas is providing unique access to high normalized plasma pressure at high plasma temperature, thereby greatly expanding the understanding of fusion plasmas. Further, the simplified magnet field coil configuration and compact geometry of the ST offer the potential of a cost-effective path to fusion energy.

*Strategic Fit of Mission Need*

The Fusion Energy Sciences Advisory Committee (FESAC) report issued October 2007 and entitled: "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy" identified three research themes prioritizing those issues that must be addressed to bridge the gap from successful ITER operation to a demonstration fusion power plant (Demo). The three themes are:

- Creating Predictable High-performance Steady-state Burning Plasmas
- Taming the Plasma Material Interface
- Harnessing Fusion Power

Due to the compact and accessible geometry of the ST configuration, the ST is particularly well suited to provide a cost effective test-bed to aid in 'Taming the Plasma-Material Interface' by investigating the impact of high heat and particle fluxes on the plasma material interface and the resulting back-influence on high-performance plasma operation. The ST is also potentially well suited to help 'Harnessing Fusion Power' by producing a high fluence of fusion neutrons in a compact and reduced-cost device with low tritium consumption. Such a facility could investigate the impact of fusion neutron irradiation on power plant components and develop the blanket technology needed for tritium fuel breeding and power extraction. Long-pulse high-performance ST facilities addressing theses themes would also provide valuable information for addressing issues related to 'Creating Predictable High-performance Steady-state Burning Plasmas'.

Additional research capabilities are needed to prepare the ST to contribute to resolution of the FESAC Themes described above. In 2008, the FESAC Toroidal Alternates Panel (TAP) prioritized the issues that must be addressed for the ST during the ITER era. The four highest priority ST issues are: startup and ramp-up, first-wall heat flux, electron transport, and magnets. The NSTX Upgrade Project described within this mission need statement document directly addresses these FESAC TAP high priority issues.

*Priority of Mission Need*

Enhanced capabilities are needed to address the FESAC TAP high priority research issues for the ST and to maintain the FES program in a scientific leadership position by providing unique toroidal fusion/plasma science that contributes to the knowledge base for ITER. The NSTX Upgrade Project objectives were supported by statements (dated May 22, 2008) from Dr. Raymond Orbach, Under Secretary for Science where he noted that "The Spherical Torus is closely related to the tokamak, and experiments planned for the next several years in the NSTX facility promise many exciting discoveries that should directly impact our ability to understand the new plasma regimes expected in ITER. The Spherical Torus may also prove to be a prototype for the next step for the U.S. domestic fusion program. Proposed upgrades for the Spherical Torus experiment at PPPL can keep this facility at the forefront of fusion science research in the world well into the future."

*Internal/External Drivers*

Not applicable.

## Capability Gap

Considerable gaps need to be filled to design next-step ST facilities with high confidence, and to contribute toroidal science of full relevance to ITER.

An important gap exists in plasma collisionality, which is a key plasma parameter influencing ST physics and performance issues including: start-up, ramp-up, sustainment, transport, and stability. The present ST collisionality is 1 to 2 orders of magnitude higher than the anticipated low collisionality of next-step STs and ITER. The NSTX Upgrade Project aims to reduce the collisionality gap by up to one order of magnitude.

Present STs operate with a confining toroidal magnetic field up to only 0.55 Tesla. This low toroidal field limits the knowledge and understanding that can be gained regarding next-step STs, which are envisioned to operate in the range of approximately 2 Tesla. The NSTX Upgrade Project aims to provide the first factor of two increase in confining magnetic field toward next-step ST parameters - in particular strongly increasing the plasma temperature and decreasing the collisionality.

A key operational issue for the next-step STs is fully non-inductive operation. For example, a Component Test Facility to test nuclear components for Demo if built would have to be a nuclear facility operating for periods of weeks at a time. Therefore, the decision for such a facility must be based on a design to operate fully non-inductively with high confidence. Present STs have achieved up to 65% non-inductive current fraction sustained for ~1 second. A ST targeting the achievement of 100% non-inductive current fraction sustained for durations sufficient for profile relaxation (up to ~5 seconds at low collisionality) will provide greatly increased confidence.

The demonstration of reduced collisionality, higher field, and also fully non-inductive operation of a ST would significantly increase the confidence of the design for next-step ST facilities, while also contributing to the development of advanced non-inductive operating scenarios for ITER.

*Other Potential Capabilities Worldwide*

There are presently three operating ST facilities in the U.S. - NSTX, Pegasus, and the Lithium Tokamak Experiment (LTX). NSTX is the only Mega Ampere (MA)-class ST facility in the U.S. and operates with powerful auxiliary heating systems (7 MW Neutral Beam Injection (NBI), 6 MW High-Harmonic Fast Wave (HHFW)) and comprehensive state-of-the-art plasma diagnostic systems. ST experimental programs have also emerged during the past 10 years in the United Kingdom (U.K.), Japan, Russian Federation, Italy, Brazil, China, and Turkey. There are now 22 experiments operational or under construction worldwide. The only other MA-class ST facility in the world is the Mega Ampere Spherical Tokamak (MAST) device in the U.K. MAST capabilities and research programs are in many ways complementary to those of NSTX. Plans to upgrade the MAST device to exceed some of the present performance capabilities of NSTX are being pursued.

*Benefits from Closing the Gap*

Next-step STs are projected to cost at least an order of magnitude more than the present ST facilities. Upgraded ST capabilities would provide the needed database to greatly improve the confidence for the design, construction, and operation of such facilities. The enhanced research capability and flexibility enabled by the NSTX Upgrade Project would also allow the ST to make unique contributions to the International Tokamak Physics Activity (ITPA) and ITER. For example, the ability to produce and investigate very high edge heat fluxes would aid in projecting and understanding divertor operation in ITER and future magnetic fusion devices.

*Impact if Gap is Not Resolved*

If ST data at higher toroidal field, plasma current, and heating power is not obtained in a timely fashion, this would adversely affect the decision to construct next-step ST facilities within the U.S. As a result, a major opportunity for U.S. leadership in fusion/plasma science in the ITER era would be forfeited. Further, opportunities to contribute new and unique ST data to the development of a predictive capability for ITER operation and the design of future fusion facilities beyond ITER would be forfeited.

*High-Level Interdependencies*

No high-level interdependencies have been identified for the NSTX Upgrade Project.

**Approach**

Physics analysis carried out during the preparation for the NSTX Five Year Program Plan for 2009-2013 indicated that access to plasma collisionality up to an order of magnitude lower than achieved in present ST devices requires a doubling of the magnetic field and plasma current, and increased heating power. Increased magnetic field strength, plasma current and pulse duration are the highest priority capabilities needed to narrow the ST gap in collisionality and non-inductive current drive. The existing HHFW on NSTX may be able to provide the needed increased heating power. Additionally, equilibrated 100% non-inductive current-drive capability is estimated to require increased current drive efficiency and controllability, which can be provided by NBI auxiliary heating systems. This could not be provided by the HHFW system.

The alternatives to fill the capability gap include the following:

1. Do nothing (maintain status quo) - This option will not meet the DOE and Office of Science mission need and strategic goals since existing ST facility capabilities are not adequate to access the reduced plasma collisionality and full non-inductive current drive needed to develop a comprehensive predictive capability for fusion science. Do nothing option also will not fully address key scientific issues for ITER, or to definitively assess or exploit the ST as a cost-effective path for fusion / plasma energy science applications.

2. Construct a new ST - Construction of a new ST facility could fill the capability gaps described above. Potential advantages of constructing a new ST facility include increased flexibility and/or design improvements. However, the design of a new ST facility would likely be very similar in size to existing ST facilities, and would utilize similar (albeit more powerful) magnet systems, power supplies, heating systems, and diagnostics. Disadvantages include cost and time for construction, and the disruption to ongoing ST research if existing ST facilities were not operated during the construction phase of a new ST facility.

3. Upgrade NSTX - Upgrading the NSTX facility could significantly narrow or close the capability gaps identified above. NSTX was designed to have upgradeable magnets, power supplies, and heating systems. Most existing diagnostic systems are compatible with these upgraded capabilities. Advantages of upgrading NSTX include cost and schedule savings from utilization of the existing NSTX facility while minimizing the

disruption to ongoing ST research. Potential disadvantages include reduced flexibility and/or capability relative to constructing a new ST device.

4. Use or collaborate with other ST facilities, such as MAST in the U.K. - No other ST facilities - including the existing MAST facility - are adequate to close the capability gaps identified above. Upgrades to the MAST device are being considered to narrow these gaps, and the upgraded MAST facility would not likely surpass present NSTX capabilities in some parameters, such as maximum toroidal field strength. However, upgrades to the MAST device would not likely enable access to higher magnetic strength, non-inductive current drive fraction, and pulse duration. Further, even the upgraded MAST capabilities are not adequate to access very high normalized plasma pressure at low plasma collisionality needed to fully understand and exploit the ST parameter regime. Finally, the MAST facility is already heavily utilized by its present research team, and access for U.S. researchers would likely be limited.

Based on the above considerations, upgrading the existing NSTX facility is the most likely path to be pursued to close ST capability gaps in a timely and cost-effective manner. The NSTX collaborative research team developed its Five Year Program Plan for 2009-2013 which was favorably peer reviewed and strongly endorsed in DOE-OFES reviews conducted on July 28-31, 2008. The review panel specifically endorsed NSTX upgrade plans which form the central elements of the NSTX Five Year Program Plan. The proposed upgrade capabilities entail a new center-stack and a second neutral beam heating system. As part of the Critical Decision (CD)-1 process, a more detailed analysis will be performed on the proposed alternatives and a selection of the alternative will be made as part of CD-1. Final decisions as to what upgrade capabilities to pursue will be made at CD-2.

The fabrication/modification and installation of these two components are the basis for the cost and schedule estimates provided below.

**Constraints**

*Technical risks*

STs have been constructed before and no foreseeable technical risks outside of those technical risks associated with construction and operation of STs are expected from this project.

*Safety Risks*

The NSTX Upgrade Project will comply with the requirements of the National Environmental Policy Act (NEPA) and its implementing regulations. Activities involving potential radiological exposures will be conducted in accordance with existing radiological safety requirements, which are in compliance with relevant DOE rules including 10 CFR 835.

It is expected that a Categorical Exclusion (CX) under Appendix B to Subpart D of the DOE NEPA Implementing Procedure Rule (10CFR1021) will be requested. The NSTX Upgrade Project will incorporate institutional Integrated Safety Management (ISM) Plan that has been approved by DOE.

*Cost Risks*

Several cost risks have been identified which could increase the cost toward the upper-cost range described in the "Resource and Schedule Forecast" section below:

- There might not be sufficient outside vendor interest or capability resulting higher costs for the project due to lack of competition.
- Escalation cost of material and labor.
- Funding and budget risks such as continuing resolutions and funding cuts.
- Design and approach changes.

*Schedule Risks*

The completion of the NSTX Upgrade Project is projected to be in FY 2013 including six months of schedule contingency, assuming the optimum funding profile in the lower range case and early in FY 2014 in the upper range case. Achievement of this schedule depends largely on receiving the necessary funding, although there is a risk that the design and manufacturing processes could take longer than anticipated.

*Legal Risks*

There are no known legal or litigation issues that would affect the planning or execution of this project.

**Resource and Schedule Forecast**

The NSTX Upgrade Project is in the pre-conceptual design stage, and design tradeoffs as well as research and development remain to be performed. Although neither a design point nor a detailed design concept have yet been established, the tasks associated with engineering design, procurement, fabrication, assembly, and testing will be similar to those of the original NSTX project and assumptions have been made based on previous experience with the NSTX project.

On this basis an evaluation has been made using the historic NSTX cost data with factors included for inflation and commodity pricing as well as relative complexity of design and fabrication, and in the case of the NBI beam box decontamination, the experience associated with the Tokamak Fusion Test Reactor Decontamination and Decommissioning Project.

*Rough Order of Magnitude (ROM) Total Project Cost estimate range*: $71M to $95M

The estimated funding profile by fiscal year for FY2009-FY2014 is:

| **Fiscal Year** | **09** | **10** | **11** | **12** | **13** | **14** |
|---|---|---|---|---|---|---|
| ROM (Lower Range) | $7M | $9M | $12M | $24M | $19M | |
| ROM (Upper Range) | $7M | $11M | $15M | $30M | $28M | $4M |

*ROM Schedule Estimate*

The NSTX Upgrade Project conceptual design activities are planned to be completed in FY 2010, and the upgrade is planned to be completed in FY 2013 in the lower range case and early FY 2014 in the upper range case. Current estimated dates for major milestones consistent with the funding profile shown above are as follows:

| | |
|---|---|
| CD-1, Approve Alternative Selection & Cost Range | FY2010 |
| CD-2, Approve Performance Baseline | FY2010 – FY 2011 |
| CD-3, Approve Start of Construction | FY2011 |
| CD-4, Approve Start of Operations | FY2013 - FY 2014 |

## Appendix I: A Glossary of Terms

| | |
|---|---|
| CD | Critical Decisions are milestones approved by the Secretarial Acquisition Executive or Acquisition Executive that establishes the mission need, recommended alternative, Acquisition Strategy, the Performance Baseline, and other essential elements required to ensure that the project meets applicable mission, design, security and safety requirements. |
| Center-stack (CS) | The cylindrical core in the center of a tokamak, which contains electrical conductors, which carry electrical current to provide the confining magnet field of the device. |
| CFR | Code of Federal Regulations |
| Collisionality | The rate at which plasma particles collide with each other as compared with the rate at which they circumnavigate the plasma. |
| Component Test Facility | A facility to test the components of a fusion reactor in a nuclear environment comparable to that of a fusion power plant. |
| Current drive | Current drive is the process of driving electrical current in a magnetic fusion device to provide part or all of the magnetic field which confines the plasma. |
| Demo | Demonstration fusion power plant |
| HHFW | High-Harmonic fast wave - an electromagnetic wave with a frequency many multiples of the characteristic cyclotron orbit frequency of ions in a magnetically confined plasma. |

| | |
|---|---|
| ISM | Integrated Safety Management. ISM at PPPL is comprised of the governing policy that safety be integrated into work management and work practices at all levels as well as the distinct policies, programs, procedures and safety culture that PPPL has developed as the structure that PPPL workers utilize in fulfilling PPPL's Environmental, Safety, and Health responsibilities. |
| ITER | ITER is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power. The partners in the project are the European Union (represented by EURATOM), Japan, China, India, Korea, Russian Federation and the U.S. ITER will be constructed in Europe, at Cadarache in the South of France. |
| ITPA | International Tokamak Physics Activity |
| Low-aspect-ratio | Low-aspect-ratio refers to aspect ratio which is in the range of 1-2, which is much lower than that of a conventional aspect ratio tokamak with A=3-5. |
| LTX | Lithium Tokamak Experiment (PPPL) |
| MA | Mega-Ampere |
| MAST | Mega Ampere Spherical Tokamak (Culham-United Kingdom) |
| Neutral Beam Injection (NBI) | The injection of high-velocity neutral atoms into a background plasma. The neutral atoms are ionized by the plasma, and then heat the background plasma, induce plasma rotation, and drive plasma current. |
| Non-inductive current drive | Plasma currents that are not produced by electric induction. Electric induction is the standard means of driving current in a tokamak. Induction is inherently transient due to engineering limitations on the magnetic coils used for induction, so non-inductive current drive is essential for making tokamaks steady-state devices. |
| NSTX | National Spherical Torus Experiment (PPPL) |
| Pegasus | Pegasus Toroidal Experiment (University of Wisconsin-Madison) |
| Plasma-material interface | The interface where plasma particles and heat make contact with a material surface in a fusion device. |
| Spherical Torus (ST) | A low-aspect-ratio tokamak, which due to its compactness, has the approximate shape of a sphere. |

| | |
|---|---|
| TFTR | Tokamak Fusion Test Reactor |
| TFTR D&D Project | Tokamak Fusion Test Reactor Decontamination and Decommissioning Project.  This project successfully removed activated and/or contaminated components from TFTR, and provided data for the decommissioning of future fusion projects. |
| Tokamak | A toroidally shaped chamber with surrounding magnetic fields for confining hot plasmas for thermonuclear fusion. |

**Critical Decision-0, Approve Mission Need**
**National Spherical Torus Experiment (NSTX) Upgrade**

## Recommendations:

The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-0, Approve Mission Need, for the National Spherical Torus Experiment (NSTX) Upgrade project.

Kim K. Chao — 2/23/09 — Yes ✓ No____
ESAAB Secretariat, Office of Project Assessment — Date

______________________________ Yes____ No____
Representative, Non-Proponent SC Program Office — Date

Karen S. Summers — 2-23-09 — Yes ✓ No____
Representative, Office of Budget — Date

[signature] — 2-23-09 — Yes ✓ No____
Representative, Environmental, Safety and Health Division — Date

[signature] — 2-23-09 — Yes ✓ No____
Representative, Safeguards & Security Division — Date

______________________________ Yes____ No____
Representative, Infrastructure Division — Date

______________________________ Yes____ No____
Representative, Grants and Contracts Division — Date

## Approval:

**Based on the information presented above and at this review, CD-0, Approve Mission Need, for the National Spherical Torus Experiment (NSTX) Upgrade project is approved.**

Patricia M. Dehmer [signature] — FEB 23 2009

Patricia M. Dehmer
Acting Director
Office of Science

Date