Historic Mechanical Engineering Site Landmark Designation

PRINCETON PLASMA PHYSICS LABORATORY
INTRODUCTION

Who among us has not looked up at the sun or at the myriad of stars on a moonless night and wondered about them? How have the stars been able to shine for millions of years, apparently without getting any fuel deliveries? Can we possibly use this same method on earth to provide for all of our energy needs? Lyman Spitzer, a Professor of Astronomy at Princeton University who was long involved in the study of very hot rarified gases (plasmas) in interstellar space, also pondered about the nature of the sun and stars and founded the U.S. Department of Energy’s Princeton Plasma Physics Laboratory, which the American Society of Mechanical Engineers has designated an ASME Historic Mechanical Engineering Site Landmark Designation. Spitzer conceived of a device that he called a “stellarator,” which would confine plasmas in a figure-eight shaped tube with external magnets. He presented this concept to the Atomic Energy Commission and, after a scientific review, received funding. Thus, magnetic fusion research at Princeton began in 1951 in a former rabbit hutch on the James Forrestal Campus. Since then, research on fusion has spread to a number of domestic and international research institutions. However, PPPL remains the lead American laboratory for fusion energy and plasma physics.

Dr. Spitzer’s first fusion device was the Model-A Stellarator, shown below along with the modest building in which the Princeton program began:
2 FUSION FUNDAMENTALS

Albert Einstein’s famous formula, \( E=mc^2 \), provides the basis for understanding that mass can be converted into energy. In fission reactions, (the process used in conventional atomic energy), heavy atoms—such as uranium—are split to release the energy that holds them together. In fusion reactions, the nuclei of light atoms—such as hydrogen—are fused or joined to produce energy.

Atoms consist of a nucleus, which carries most of the mass, surrounded by negatively charged electrons. The nucleus has a positive electrical charge that is balanced by the electrons’ negative charge so that the atom as a whole is electrically neutral. All atomic nuclei contain particles called protons, and all except one form of hydrogen also contain neutrons.

Deuterium and tritium, isotopes of hydrogen, are the easiest nuclei to fuse, and are the most likely fuel for fusion energy production.

The figure below shows three isotopes (i.e. different versions) of hydrogen. The isotopes all have the same atomic number (number of protons), but a different number of neutrons. The Deuterium-Tritium (D-T) fusion reaction is illustrated below. Note that electrons are not shown in this diagram, because the electrons are stripped from the nuclei in the hot plasma.

The fusion process appears easy but getting nuclei to fuse is extremely difficult due to their positive electrical charges that cause them to repel each other. The nuclei must be forced together at extremely high speeds (i.e., at high temperatures) so that they do not merely bounce off each other but are forced to fuse.

The tremendous sizes and masses of the sun and stars, with their corresponding high gravitational forces, create the natural conditions for fusion to occur. The nuclei are well confined by gravity, heated by gravitational compression, and confined for sufficiently long periods as they travel within the star’s tremendous volume. This provides very adequate conditions for a number of different types of fusion reactions to occur. Our sun has a plasma diameter of ~1.4x10⁹ m., and gravitational compression produces plasma temperatures of ~15 million C. The billions of stars stand in testimony that fusion is not just a scientist’s dream — it is seen throughout the heavens!

The advantages (and reasons for the strong worldwide interest) in fusion are many:

- The major fuel, deuterium, can be readily extracted from ordinary water, which is available to all nations. The surface waters of the earth contain more than 10¹² tons of deuterium, an essentially inexhaustible supply. The tritium required would be produced in the reactor from lithium, which is available from land deposits or from seawater, which contains thousands of years’ supply. The worldwide availability of these materials could eliminate international tensions caused by the current imbalance in fuel supply for power production.
The amounts of deuterium and tritium in the fusion reaction zone will be so small that a large uncontrolled release of energy would be impossible. In the event of a malfunction, the plasma would strike the walls of its containment vessel and cool.

Since no fossil fuels are used, there will be no release of chemical combustion products because they will not be produced. Thus, there will be no contribution to global warming or acid rain.

Similarly, the radioactive products that are formed are far less dangerous and less long-lived than fission products, reducing the handling and disposal problem. Radioactivity will be produced by neutrons interacting with the reactor structure, but careful materials selection is expected to minimize the handling and ultimate disposal of such activated materials.

**Magnetic fusion energy** (MFE) relies on strong electromagnets to create a “magnetic bottle” to substitute for the gravitational bottle of the stars and our sun. First, a plasma is formed by heating a gas to the point that some or all of the electrons are stripped away from its atoms. This charge separation makes it possible to control the motions of the electrons and atomic nuclei (ions) with magnetic fields.

A variety of methods, including high electrical currents (in the millions of Amperes), radio frequency heating, and energetic beams of neutral atoms are used as a substitute for gravitational compression to heat the plasma. The so-called Lawson Criteria quantifies the much more challenging conditions required for net fusion power from a terrestrial fusion reactor: a plasma temperature of 100-200 million degrees C, a central plasma density of $1-2 \times 10^{20}$ particles/cu. m., and a confinement time of at least one to two seconds. The quest of research to develop magnetic fusion energy is to create an efficient magnetic bottle to confine the plasma, and efficient heating to make practical, cost effective energy possible.

MFE research at Princeton has focused on two major concepts, the *stellarator*, which was the concept invented by Lyman Spitzer, and the *tokamak*, which was invented in the 1950s by Soviet physicists Igor Tamm and Andrei Sakharov. [https://en.wikipedia.org/wiki/Tokamak]. Research at Princeton began with stellarators with figure-eight shaped plasmas. The stellarator’s major advantage is that steady state operation—so important for fusion-based power generation—is an inherent feature of this confinement method. The difficulty found in the early stellarators was inadequate plasma confinement. When better performance was reported for tokamaks in the late...
1960s, Princeton converted its Model C Stellarator to a tokamak in 1968 (see p. 8). Tokamaks have performed well. In fact, the two experiments operating with fusion fuel of deuterium and tritium to date — PPPL’s Tokamak Fusion Test Reactor (TFTR) and UK’s Joint European Torus (JET) — are tokamaks. The downside of the tokamak is that steady state operation is difficult to achieve. Tokamaks utilize high currents flowing in the plasma for two purposes: to partially heat it, and to aid in its confinement. In present tokamaks, this current is induced by a transformer, which is time-limited by the transformer’s magnetic flux swing. Additionally, tokamaks are prone to plasma disruptions—the sudden loss of plasma current (in the millions of amps) due to plasma instabilities that are still not fully understood. During a disruption, the current flowing in the plasma is suddenly induced in nearby conducting structures, resulting in tremendous electromechanical forces. Structures of tokamaks must be carefully engineered to resist these very high-level forces—this is a significant driver in tokamak design.

A major internationally supported tokamak project, ITER, is currently underway in southern France [www.ITER.org]. ITER will take magnetic fusion research into the burning plasma regime, where fusion conditions of density and temperature are such as to provide more than half of the heating power from the self-heating by nuclear reactions. PPPL is involved in the development of diagnostics, first wall components, and the steady state power system for ITER.

Another variant of the tokamak is the spherical tokamak (ST) which reduces the size of the core of the torus as much as possible, producing a plasma, which is almost spherical in shape. The advantage of this spherical shape is good performance at reduced magnetic field in the center of plasma. PPPL’s present major experimental device, NSTX-U (Upgrade), is a spherical tokamak.

Since the early days of stellarator research, engineers and scientists have made significant advances in understanding stellarators. Accordingly, two major stellarators, the Large Helical Device (LHD) in Japan and Wendelstein 7-X (W7-X) in Greifswald, Germany have been constructed. The LHD has been operating since 1998 while W7-X, which achieved first plasma in December 2015, is one the world’s most advanced operating fusion experiments. This device uses carefully engineered 3-dimensional fields to produce plasma confinement far superior to the original figure-eight stellarators. The researchers plan to operate it for plasma durations of up to 30 minutes as a major step to demonstrating the potential for steady state operation.
3 STELLARATORS AND TOKAMAKS

The figures below illustrate the basic differences between the three major types of magnetic fusion energy devices that are mentioned in the following sections. Each concept presents unique challenges from an engineering viewpoint.

**Early Stellarators:** The plasma confinement chamber in Spitzer’s early stellarators was race track-shaped when viewed from the top, with a 180-degree twist in one end to form a figure eight, as shown in this photo.

**Modern stellarators** like Greifswald, Germany’s W7-X Stellarator use 3-dimensional configured confinement magnets to generate an improved stellarator field. Note the array of shapes in the blue confinement magnets. (Figure: Max-Plank Institut fur Plasmaphysics).

**Tokamaks:** This figure shows the major components of a tokamak: the Toroidal Field (TF) coils, which provide the confinement magnetic field; the inner poloidal coils (solenoid), which serve as the primary of the transformer that induces the current into the plasma secondary conductor; and the outer poloidal field coils, which are required for plasma shaping and holding the plasma in equilibrium. [from https://en.wikipedia.org/wiki/Tokamak]

**Spherical Tokamaks:** This is an illustration of PPPL’s National Spherical Torus Experiment (NSTX). Notice the low aspect ratio as compared to the tokamak shown above. This results in a compact device with higher ratios of plasma pressure when normalized by the magnetic field and plasma current.
4 MECHANICAL ENGINEERING’S ROLE IN FUSION DEVELOPMENT

Mechanical engineering plays a key role in fusion development, drawing upon a broad array of engineering disciplines and sub-disciplines. These include systems engineering, structural analysis, fatigue and fatigue crack growth analyses, dynamic analysis, fluids and heat transfer and cryogenics, materials that include metals and composites, and manufacturing and engineering project management. Engineers at PPPL apply a wide variety of tools, requiring state-of-the art knowledge and skills in mechanical engineering. They interact with physicists, as well as their engineering colleagues at PPPL, with industrial subcontractors, and with the many institutions with which PPPL collaborates. Mechanical engineers were especially prominent in PPPL’s coil shop. In 1974, a large shop was located on the south side of the James Forrestal Campus in a large, hangar-like building that was formerly part of the Princeton-Penn Accelerator. This facility, shown in the photo below, produced the very large electromagnetic coils for PLT, PDX, S-1, TFTR and ATF (ORNL). Initially the coil shop was located in the “rabbit hutch” shown on p. 1. The coil group had 10 engineers and 22 technicians at its peak. The coil shop was decommissioned as a separate unit in 1986, but staff from the original group have continued to design and produce coils as needed for the Fusion Program.
5 HISTORIC OVERVIEW OF KEY PPPL EXPERIMENTAL DEVICES

Following is an overview of just some of the fusion research devices developed at PPPL. In addition to major devices, PPPL has also developed (and currently operates) some smaller devices aimed at specific areas of fusion research such as diagnostics development, liquid metal walls, and magnetic reconnection. See https://www.pppl.gov/about/history/timeline for additional details. [Evolution of Coil Design and Manufacturing at PPPL; James H. Chrzanowski, 9/24/2014]

Model C Stellarator (1957 - 1969) A Major Atoms for Peace Project to Study Fusion

In the early 1950s, a sequence of small experiments based on Lyman Spitzer’s stellarator concept were built at Project Matterhorn to study the confinement and heating of plasmas confined in a stellarator magnetic field. The plasma performance in these small stellarators was limited by plasma instabilities and associated turbulence. The design of a larger Model C stellarator to extend the experimental studies to larger size and higher plasma temperature began in 1957 as part of the Atoms for Peace Program. This device was roughly three times larger than previous stellarators with a minor radius of 5 cm and a strong magnetic field of 50 kilo-gauss. The Model C Stellarator shown in the photo began operation in 1961 following a four-year design and construction effort involving PPPL engineers and physicists, and industrial participants from Allis Chalmers, RCA and Westinghouse. Many of the industrial engineers remained at PPPL and formed the basis of a strong mechanical engineering capability for many decades. The experiments confirmed that plasma loss due to turbulence in the Model Stellarator was still limiting plasma confinement and temperatures that were too low to be of interest for fusion energy.
1968–1969 Soviet Scientists Announce Plasma Temperature Breakthrough

The T-3 tokamak in Moscow achieved plasmas with reduced turbulence, and electron temperatures greater than 10 million °C. Immediately after these results were announced, PPPL engineers began to convert the Model C stellarator to the Symmetric Tokamak, ST (photo on the left). This was achieved in a remarkably short eight months! The ST tokamak, with advanced plasma diagnostics and digital data acquisition and analysis, quickly confirmed the Russian advance and extended the detailed results over the next three years. The ST results validated U.S. government plans to aggressively pursue an expanded tokamak program.


The Floating Multipole-1 (FM-1) was designed to study the turbulence caused by trapped particles in a toroidal geometry similar to that of the outer region of a tokamak. In addition, FM-1 had a poloidal divertor to study the flow and removal of plasma impurities. Although the plasmas in FM-1 were low temperature (0.2–1 million °C) and density (~10^17 particles/m^3) that was sufficient to study the properties and cause of the plasma turbulence. FM-1 replaces the plasma current of a tokamak with the current in a superconducting levitated coil (375 kilo-amp-turns, 850 lbs.) located inside the vacuum vessel and surrounded by the confined plasma. This design required innovative approaches to the construction of the superconducting Nb3Sn coil with integrated cold thermal storage contained in a cryogenic vacuum-tight flask or “dewar.” Levitation of this coil was a challenge since suspension in a static magnetic field
is inherently unstable. This required a complex system of stabilizing coils located inside the vacuum vessel. Light beams detected the position of the superconducting coil through processing in a state-of-the-art 1970s digital computer feedback system; this allowed the 850-pound coil to be suspended in space within a millimeter for up to 10 hours. At the end of the 10-hour experimental run, engineers inserted four pneumatically actuated catchers into the vacuum vessel to restrain the coil and inserted a cryogenic transfer pipe into the dewar to remove the gaseous helium pressure built up inside it. This work was done while maintaining high vacuum in the plasma confinement region. The figure above shows the internal components of FM-1 with the top of the main vacuum vessel removed. Also shown is the toroidal superconductor dewar, with four catchers engaged to support it, and the stabilization coils. In addition, the central vertical column is the inner leg of a normal conducting coil that produces a toroidal magnetic field similar to that in a tokamak. Each of the 72 turns of the toroidal field coil had two joints held together with hydraulic clamps that allowed the device to be assembled around the superconducting ring coil. In addition, FM-I had a poloidal divertor to study the flow and removal of plasma impurities. The device was constructed in four years. The innovations on FM-1 were a truly remarkable mechanical engineering achievement in 1971!

1971-1975 U. S. Fusion Research Activities Rapidly increase

The continuing Cold War competition with the Soviet Union and the first hints of a looming energy crisis increased interest and funding for developing high-technology energy capabilities in the U. S. The U. S. fusion budget in FY2015 began a rapid increase from $154M in 1971 to $1.02 Billion in 1977. In response, PPPL initiated the rapid construction of two tokamaks in 1971: the first, named ATC, to explore methods for heating tokamak plasmas to the temperatures required for fusion and the second larger tokamak, named PLT, to determine the confinement properties of a plasma at near reactor temperatures.
Adiabatic Toroidal Compressor (ATC, 1971-1976)
The ATC was the first, and smaller of the two devices. It was designed to test heating a tokamak plasma to high temperatures by means of magnetic compression (rapid reduction of the plasma volume). This rapid compression required a vacuum vessel with high electrical resistance contrary to previous tokamak designs that had copper shells surrounding the plasmas to hold the plasma current ring in equilibrium. In ATC, a separate coil system held the plasma current ring in place and the plasma current was induced by an air-core transformer instead of the iron-core transformers used on Model C, Symmetric Tokamak and earlier Russian tokamaks. ATC also provided early tests of using neutral beams to heat tokamak plasmas. These innovative features introduced several new challenges for mechanical engineers, whose successful solutions allowed these advanced features to be incorporated into later tokamak designs.

The second and larger of these two devices, Princeton's Large Torus (PLT) (1972-1988) had a primary goal to carry out the first study of magnetically confined plasmas at temperatures approaching fusion reactor levels. Several theoretical models predicted that turbulence caused by trapped ions would prevent the tokamak plasma from reaching reactor temperatures. A range of auxiliary heating methods, including neutral beam injection and radio-frequency waves were studied. Note the large external stainless-steel torque frame that counteracted forces that could turn the toroidal coil sideways. The toroidal field and poloidal field coils, and most of the vacuum vessel and structure were engineered and fabricated at PPPL. The PLT construction was completed in four years.
This slide shows the TF coil being fabricated. PLT had many poloidal field (PF) coils, as shown in the layout in the following slide. These coils were cut into 180-degree segments, and then joined by induction brazing in place around the inner leg of the assembled TF coil array. This was an innovative approach, which required development of specialized tooling and fabrication methods. The PLT device, constructed in three years, began operation in December 1975.

In August 1978, the PLT had achieved plasma temperatures of 65 million °C, which was sufficient to enter the reactor temperature regime. This confirmed the wisdom of the decision to build the next larger tokamak, the Tokamak Fusion Test Reactor, TFTR, already under construction at PPPL (described in a later section). PLT continued to run another eight years exploring ion cyclotron radio frequency as another method to heat plasmas to reactor temperatures.

The goal of PDX was to address impurity control using magnetic divertors to isolate the core plasma from direct contact with the wall. Impurities such as oxygen, carbon, and iron, which enter the plasma when it interacts with the vacuum vessel wall, would increase energy losses and adversely affect the operation of a fusion reactor. PDX was constructed in four years and began operation in 1978. Kaman Aerospace fabricated the TF coils. The vacuum vessel, PF coils, in-vessel coils, and structure were fabricated by PPPL, with the assistance of subcontractors. PDX’s design, with its stainless-steel vacuum vessel and in-vessel divertor coils, required that the toroidal coils be designed to be installed around the vessel. Accordingly, the 18 toroidal field (TF) coils had joints at the top and bottom to permit installation, as shown in the adjacent slide. The joints were held together with 36 hydraulic clamps. The mechanical engineering on the very complex PBX was a milestone accomplishment. PDX operated with toroidal magnetic fields up to 24 kilo-gauss, plasma currents of 500 kiloamps, 7 million watts of neutral beam heating and ion temperatures of 70 million °C. PDX validated Spitzer’s 1950 divertor concept and demonstrated significant reduction of heavy impurities that can cause significant radiation loss from the core of a fusion plasma.
In the mid-1980s, the device was upgraded to the Princeton Beta Experiment (PBX) and later modified again to PBX-M. Modifications included fabricating vacuum-jacketed coils within the vacuum vessel, as seen in this slide, modifying internal structures, and adding passive stabilizer plates.

The Tokamak Fusion Test Reactor (TFTR) (1976-1997)

In the mid-1970s, as tokamak results around the world produced encouraging results, major international fusion programs (U.S., Europe, Japan, and Soviet Union) decided to build a large tokamak as the next step toward magnetic fusion energy. These were bold steps with a 10-fold increase in plasma volume and plasma current relative to previous tokamaks. The U.S. was to build the Tokamak Fusion Test Reactor (TFTR) at PPPL. The TFTR Construction Management Plan was officially approved in March 1976 with the mission to:

1. Study plasma physics of large tokamaks
2. Gain experience with reactor scale engineering
3. Demonstrate D-T fusion energy by the production of 1-10 million joules of fusion energy.

Groundbreaking for TFTR took place in 1977. The massive size and complexity of the device required significant industrial involvement: Ebasco and Grumman Aerospace were the prime subcontractors for the project: Westinghouse fabricated the TF coils, Asea/Brown Boveri (ABB) fabricated the inner poloidal field coils, and PPPL fabricated the large diameter outer PF coils.
The photos below show one of the PF coils during fabrication in the PPPL coil shop and the beginning of the TFTR toroidal field coil assembly.

Among TFTR’s many achievements:

- TFTR was constructed in 6.5 years and was the first of the world’s three large tokamaks to begin operation in December 1982.

- In 1986, TFTR set the still-standing world’s record for the Lawson fusion parameter, fuel density x energy confinement time of $1.5 \times 10^{20} \text{ m}^{-3} \text{ sec}$, and was the first magnetic fusion experiment to achieve a fuel temperature of more than 200 million °C—the temperature required for a fusion power plant.

- From 1993 to 1997, TFTR was the first magnetic fusion device to operate with fusion fuel—a 50/50 mix of deuterium and tritium. TFTR extended the fuel temperature record to 520 million °C, produced a record of 10.7 million watts of fusion power, 7.5 million joules of fusion energy and conducted the first experiments on the effects of fusion alpha particles in a magnetically-confined plasma.

- TFTR operated beyond original engineering parameters using DT fuel with high availability and no safety incidents for over three years of tritium operation. The toroidal field coils achieved 59 kilo-gauss compared with the original design requirement of 52 kilo-gauss and the neutral beams provided 40 million watts compared to the original requirement of 33 million watts, a testament to the excellence of the mechanical engineering staff at the PPPL.

Following three years of more than 1,000 successful D-T experiments, TFTR was safely disassembled and removed in 2002 by PPPL engineers.
and technicians. This was completed on schedule and under budget, demonstrating a number of innovative methods of decommissioning and decontaminating a D-T-fueled fusion device and freeing this advanced facility for future experimental facilities. TFTR is the first and only D-T fusion device to be decommissioned to date.

The National Compact Stellarator Experiment (NCSX) (1998-2008)

PPPL, in conjunction with Oak Ridge National Laboratory (ORNL), began a study of a compact stellarator concept in 1998. Although the project was discontinued in 2008 before it was completed, this project significantly advanced the team’s state-of-the-art engineering expertise in fields including complex CAD modeling, “almost paperless” CAD-CAM fabrication methods, structural analysis of intricately-shaped parts with complex electromagnetic loading, and advanced mechanical measuring methods. Like modern stellarators, its coils and vacuum vessel were shaped to provide a 3-dimensional stellarator magnetic confinement configuration. The geometry of the stellarator plasma and its coils was designed by PPPL physicists using high-performance computing to optimize properties that govern plasma performance. The NCSX was designed to test a unique physics design strategy known as magnetic “quasi-axisymmetry,” in which the motion of plasma particles is the same as in a tokamak. The aim was to obtain the favorable properties of stellarators: stability, and inherent ability to operate in steady state in a device with tokamak-like performance, blending the favorable performance characteristics of both concepts. PPPL/ORNL engineers worked closely with subcontractors Energy Industries of Ohio (EIO), Major Tool and Machines of Indianapolis, and MetalTek International of Pevely, Mo., on the development of the design and fabrication methods of the large stainless-steel castings on which the modular coils are wound at PPPL.
NCSX’s 3-dimensional magnet system requires (18) modular coils in (three) distinct shapes. They are the most challenging ever produced by the PPPL coil shop. All were successfully manufactured, realizing tolerances of 0.5 mm over around 90 percent of the coil circumferences.

The highly-shaped vacuum vessel segments, shown in the following photo of fabricated components, were made from press-formed panels welded together by Major Tool and Machine.

The complex geometries of the modular coils and vacuum vessel were challenging to measure. This required PPPL to develop the in-house capability to use laser scanners and multi-link measuring systems and software. These capabilities are now integral tools at PPPL.

**The National Spherical Torus Experiment (NSTX) (1996-2010)**

NSTX first began operation in 1999. Its innovative almost spherical-shaped plasma may have several significant advantages, the most important being the ability to confine a higher plasma pressure for a given magnetic field—important factors for smaller, more economical fusion reactors.

To achieve this shape, the central portion of the toroidal field (TF) coil must be very compact. In NSTX, custom copper extrusions were arranged in a two-layer configuration and bonded together with fiberglass and epoxy, as shown
in the cross-section of the TF inner bundle in the following figure. The outer “legs” of NSTX are connected to the central bundle by flexible high current straps to allow for thermal growth of the central TF assembly. Spline connections between the TF bundle react with the electromagnetic torque developed in the center column through the vacuum vessel.

NSTX had a very successful experimental program that demonstrated the capabilities of a spherical tokamak device. A list of NSTX’s many accomplishments are presented at https://nstx-u.pppl.gov/accomplishments.

**NSTX Upgrade (2012-present)**

Building on NSTX’s success, work was begun on an upgrade to expand its experimental capabilities:

<table>
<thead>
<tr>
<th>NSTX Upgrade Performance Comparison</th>
<th>NSTX</th>
<th>NSTX-U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current, Ip [MA]</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Toroidal field Bt [T]</td>
<td>0.55</td>
<td>1.0</td>
</tr>
<tr>
<td>Pulse length [s]</td>
<td>1.0</td>
<td>5.0</td>
</tr>
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A number of design changes, vessel reinforcements and structural changes had to be made to handle the higher forces associated with the upgrade as shown in the figure below.

A key component of the upgrade is the center stack assembly, which consists of the center legs of the TF coils and the ohmic heating solenoid that is wound directly on it. This photo shows the completed assembly.

The electrical connections to the center stack is a critical area. This was an area of focus in which a number of design changes were made to accommodate the higher currents and forces of the upgrade while also improving reliability. High-strength copper chrome zirconium lead extensions were friction stir welded to the high conductivity oxygen-free copper TF inner conductors. The strong copper permits high preload pressure, important for electrical joint conductivity, while the high conductivity copper in the long inner conductors reduces resistance and temperature rise.
The inner TF flex joint that makes the high-current electrical connection to the center stack was electric discharge machined from a copper chrome zirconium plate. It was fatigue tested to five times life.

NSTX-U began experimental operation in the summer of 2015. During its first 10 run weeks, diagnostic and control systems were commissioned, the H-mode accessed, magnetic error fields identified and mitigated, and the first physics research campaign carried out. During that run period, several machine component-related operational issues arose, the most serious being an electrical short in one of the poloidal field (PF) coils. This coil failure required that the machine be shut down. Considering the series of component-related issues, a NSTX-U Recovery Project has been initiated. Its goal is to address the causes of the issues and coil failure, and make appropriate changes in designs, procedures, hardware, and operation.

6 THE HISTORY AND HERITAGE PROGRAM AT ASME

Since the invention of the wheel, mechanical innovation has critically influenced the development of civilization and industry as well as public welfare, safety and comfort. Through its History and Heritage program, the American Society of Mechanical Engineers (ASME) encourages public understanding of mechanical engineering, fosters the preservation of this heritage and helps engineers become more involved in all aspects of history.

In 1971, ASME formed a History and Heritage Committee composed of mechanical engineers and historians of technology. This committee is charged with examining, recording and acknowledging mechanical engineering achievements of significance. For further information, please visit http://www.asme.org.
ASME LANDMARK DESIGNATIONS

There are many aspects of ASME’s History and Heritage activities, one of which is the Landmarks Program. Since the History and Heritage program began, 267 artifacts have been designated throughout the world as historic mechanical engineering landmarks, heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general.

The Landmarks Program illuminates our technological heritage and encourages the preservation of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers. It also provides reminders of where we have been and where we are going along the divergent paths of discovery.

ASME helps the global engineering community develop solutions to real world challenges. ASME, founded in 1880, is a not-for-profit professional organization that enables collaboration, knowledge sharing and skill development across all engineering disciplines, while promoting the vital role of the engineer in society. ASME codes and standards, publications, conferences, continuing education and professional development programs provide a foundation for advancing technical knowledge and a safer world.

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The Princeton Plasma Physics Laboratory has long been the site of research achievements in the quest to develop controlled fusion reactions. Engineers have designed, built and operated a series of fusion energy devices known as stellarators, tokamaks, and spherical tokamaks. These facilities utilize strong magnetic fields to contain hydrogen isotopes many times hotter than the core of the sun to produce fusion reactions that release energy that could be harnessed for the benefit of all humankind.

The intense magnetic fields produce high forces on structures that must remain precisely aligned. Engineers here developed new fabrication techniques that produced the tolerances required to achieve world-record plasma performance. This laboratory continues to be at the forefront of the world’s fusion energy research.