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# THE ENGINEERING DESIGN OF THE TOKAMAK PHYSICS EXPERIMENT

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## HISTORY

In the fall of 1991 the Department of Energy fostered the organization of an activity to establish the mission and basic design characteristics of the next major tokamak facility to be constructed within the U. S. fusion program. This process included a design team, which provided input to a National Task Force of fusion physicists and engineers chaired by John Sheffield, Director of the Oak Ridge National Laboratory (ORNL) fusion program. A special panel of the Fusion Energy Advisory Committee (FEAC Panel 2) was chartered by DOE to advise the Department relative to the recommendations of the National Task Force. The resulting project was titled the Tokamak Physics Experiment (TPX). During the spring of 1992 this process established the mission for TPX and basic design characteristics, including the fact that the magnet system would be based on superconducting magnet technology. In the fall of 1992 the Department gave formal "Key Decision" approval of the "mission need" for the project, and the conceptual design began in October 1992, leading to a Conceptual Design Review (CDR) in March 1993 chaired by James Callen of the University of Wisconsin. The CDR confirmed the adequacy of the design for proceeding with the project and provided valuable advice related to the improvement of the design and management systems. The organization of the project was refined in December 1993. One organizational improvement was the establishment of two advisory committees: the National TPX Council and the Program Advisory Committee. A DOE Independent Cost Estimating (ICE) activity was initiated at the time of the CDR and completed in June 1993. The CDR and ICE recommendations related to project cost were factored into the TPX cost baseline during the summer of 1993. In December of 1993 the Department gave the "Key Decision" approval for the start of Title 1 design. The Title 1 design formally began in October 1993.

## I. MISSION

"The mission of the Tokamak Physics Experiment (TPX) is to develop the scientific basis for a compact and continuously operating tokamak fusion reactor." The objectives that support the mission are:

- Optimize plasma performance through active control of the current profile and of plasma-wall interactions, and by advanced plasma shaping --- leading to a compact fusion reactor.
- Achieve this optimization using techniques for non-inductive current drive and profile control that are consistent with efficient continuous operation of a tokamak fusion reactor.
- Demonstrate the integration of optimized plasma performance and efficient continuous operation in fully steady state tokamak plasmas.

The physics basis for the mission and supporting objectives is discussed in detail in the companion paper by G. H. Neilson.

## II. ORGANIZATION

The TPX Project is a focused national effort involving the coordinated resources of a large part of the DOE's fusion program. Although the Princeton Plasma Physics Laboratory (PPPL) is responsible for the project and will be the site for construction of TPX, the Project includes, as participants, many of the U. S. fusion research laboratories and universities.

Figure 1 shows the overall management structure for the TPX Project. The authority of the Director of PPPL flows to the two key positions; the TPX Program Director and the TPX Project Director. The TPX Program Director has management responsibility for developing the mission, physics objectives and program requirements of TPX. The TPX Project Director has management responsibility for project execution, including engineering design, physics/engineering interface, and resource management.

The Project Physics Manager and the Project Engineer head the main elements of the TPX line organization. Project Physics is responsible for the development of the physics design requirements and analysis activities in support of TPX design and construction. The Project Engineer reports to the TPX Project Director and is

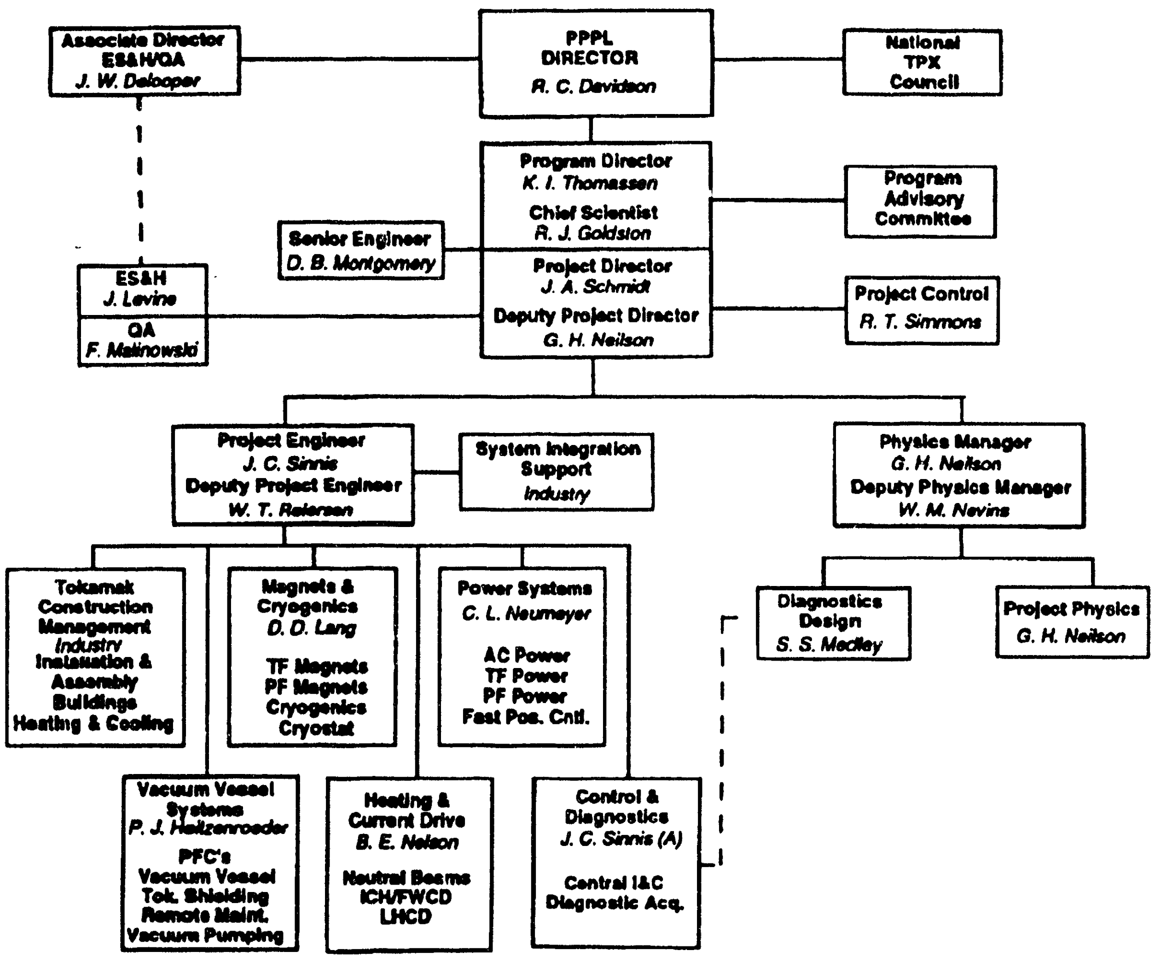


FIGURE 1. ORGANIZATIONAL STRUCTURE FOR THE TPX PROJECT.

Two advisory committees have been created to provide broad fusion community participation in TPX. These are the National TPX Council reporting to the Director of PPPL, and the Program Advisory Committee (PAC), which advises the TPX Program Director. The National TPX Council participates in decisions relating to mission, technical scope, and cost and schedule, and provides advice on the management and execution of the Project. The PAC is established to review proposed plans and schedules for experimental research on the TPX facility.

responsible for developing the TPX design and overseeing its construction to meet the TPX Mission and specific objectives. He is assisted by a Deputy Project Engineer. The Deputy Project Engineer is also delegated oversight responsibility for the Systems Integration Support (SIS) subcontractor. Several Engineering Managers report to the Project Engineer. In the line organization, the responsibility is grouped according to hardware and technical expertise (and to minimize interfaces) with a lead Engineering Manager designated to coordinate the scope within the assigned subsystems.

The Tokamak Construction Management (TCM) function will be assigned to an industrial contractor. The TCM scope includes responsibility for conducting constructibility reviews, procurement of conventional components and facilities, installation of all hardware, and support of the integrated systems testing program.

In addition to the line organization, the TPX Project Engineer has the Systems Integration Support (SIS) group reporting to him in a staff function. The SIS group will consist of a team from industry led by an industrial manager. The scope of the SIS contract includes, but is not limited to the following activities:

- System Requirements Definition;
- Configuration Management and Change Control;
- Document and Drawing Control;
- Configuration Development and Interface Control;
- Plant Design and Integrated Systems Modeling;
- Architect/Engineering Services.

The Project Control Manager and his organization, reporting to the Project Director, are responsible for all project support operations.

## III. REQUIREMENTS

The mission and physics objectives for TPX lead to the basic requirements and associated features for the device and in turn to the specific operating parameters.

The objective of studying plasma behavior under conditions approaching continuous operation leads to the requirement that TPX operate with very long pulses, if needed. Based on these considerations the TPX tokamak itself is being designed for continuous operation with the baseline ancillary systems being provided to support 1000 second pulses. If it proves necessary to increase the pulse length, the ancillary systems can be upgraded for the pulse length required. The plasma heating systems used on TPX have been chosen to provide both global and localized plasma current drive to sustain the current during long pulse operation and shape the current profile for discharge stability control.

The need for advanced tokamak modes of operation has lead to the requirement for flexible plasma shaping, and single and double null operation. Also required is flexibility to accommodate high beta over a wide range of profile shapes. This is an important design driver for the poloidal field magnet system.

The improved confinement associated with deuterium relative to hydrogen operation has lead to the requirement that the facility be designed to accommodate the neutron fluence associated with deuterium operation. This leads to requirements for reduced activation materials, to maximize personnel access during early operation, and remote maintenance later in the operating phase. In addition, a neutron shield is necessary between the plasma and the magnets to minimize the nuclear heating of the cold structure. This shield has the added benefit of minimizing the activation outside the vacuum vessel to facilitate hands on maintenance in these regions.

## IV. PARAMETERS

Table 1
TPX Machine Parameters

| | Baseline | Upgrade | |
|---|---|---|---|
| Toroidal Field, $B_T$ | 4.0 | | T |
| Plasma Current, $I_P$ | 2.0 | | MA |
| Pulse length | 1,000 | >>1,000 | s |
| Major Radius, $R_0$ | 2.25 | | m |
| Minor radius, a | 0.50 | | m |
| Aspect ratio, R/a | 4.5 | | |
| Elongation, $\kappa_X$ | 2.0 | | |
| Triangularity, $\delta_X$ | 0.8 | | |
| Neutral beams, $P_{NB}$ | 8 | 24 | MW |
| ICRF, $P_{IC}$ | 8 | 18 | MW |
| Lower hybrid, $P_{LH}$ | 1.5 | 3.0 | MW |
| DD neutron budget | $6x10^{21}$ | | $yr^{-1}$ |
| Peak DD neutron rate | $5x10^{16}$ | $7.5x10^{16}$ | $s^{-1}$ |

The general parameters for the TPX tokamak and supporting systems are given in Table 1. As stated above the tokamak will be designed to operate continuously; however, the ancillary systems will be initially provided to support a 1000 second pulse. These systems can be upgraded if needed to support longer pulses or continuous operation. The toroidal field, plasma current and shaping parameters lead to an expected plasma performance that is in the range of the Tokamak Fusion Test Reactor (TFTR). While the level of the toroidal field supports the achievement of a significant plasma performance, it is in a range that can be accommodated by conductor technology with a minimum of conductor development. The significant plasma elongation results in unstable plasma vertical motion that must be stabilized by a combination of passive conducting structures and active feedback coils. The compliment of heating and current drive systems provide broad heating (neutral beam) and more localized heating (ICRF & Lower Hybrid) for temperature (pressure) profile control. This system provides both ion and electron heating. In addition, this complement of current drive systems provide a similar broad and localized current drive capability to sustain the plasma current for long pulses and for current profile control to facilitate the stabilization of plasma MHD activity. This system can also be used to drive plasma rotation and support plasma diagnostics. Provisions will be made to accommodate upgrades to the heating and current drive systems to the maximum values listed if needed. The neutron fluence associated with the required deuterium operation is a significant factor in the design, since it leads to a requirement for remote maintenance of equipment inside the vacuum vessel and the desire to use low activation materials in this region. The neutronics analysis of TPX is discussed in detail in the accompanying paper by S. L. Liew.

## V. CONFIGURATION

The TPX configuration summarized here is discussed in detail in the accompanying paper by T. G. Brown. Figure 2 shows the TPX tokamak configuration. The plasma facing components for TPX feature carbon composites for surfaces with a direct line of sight to the plasma. In general the carbon is backed by water cooled copper. The requirements for remote maintenance of this hardware lead to the need to modularize internal systems where possible. Toward this end the divertor hardware will be installed and remove in sizable modules.

compared to the magnetic time constant of the passive structures. Coils will be installed behind the passive structures for this purpose. Although it would be more convenient to install these coils outside the vessel, it was determined that such a configuration would result in too high an electro-magnetic heat load to the cold magnet structure.

The remote maintenance equipment will be installed through a port onto rails that are imbedded in the outer passive plates. If the internal hardware is remotely removed then the activation levels of the titanium vacuum vessel will be low enough to facilitate personnel access to the vessel for disassembly if necessary. The remote maintenance and shielding system is described in detail in the accompanying paper by M. J. Rennich.

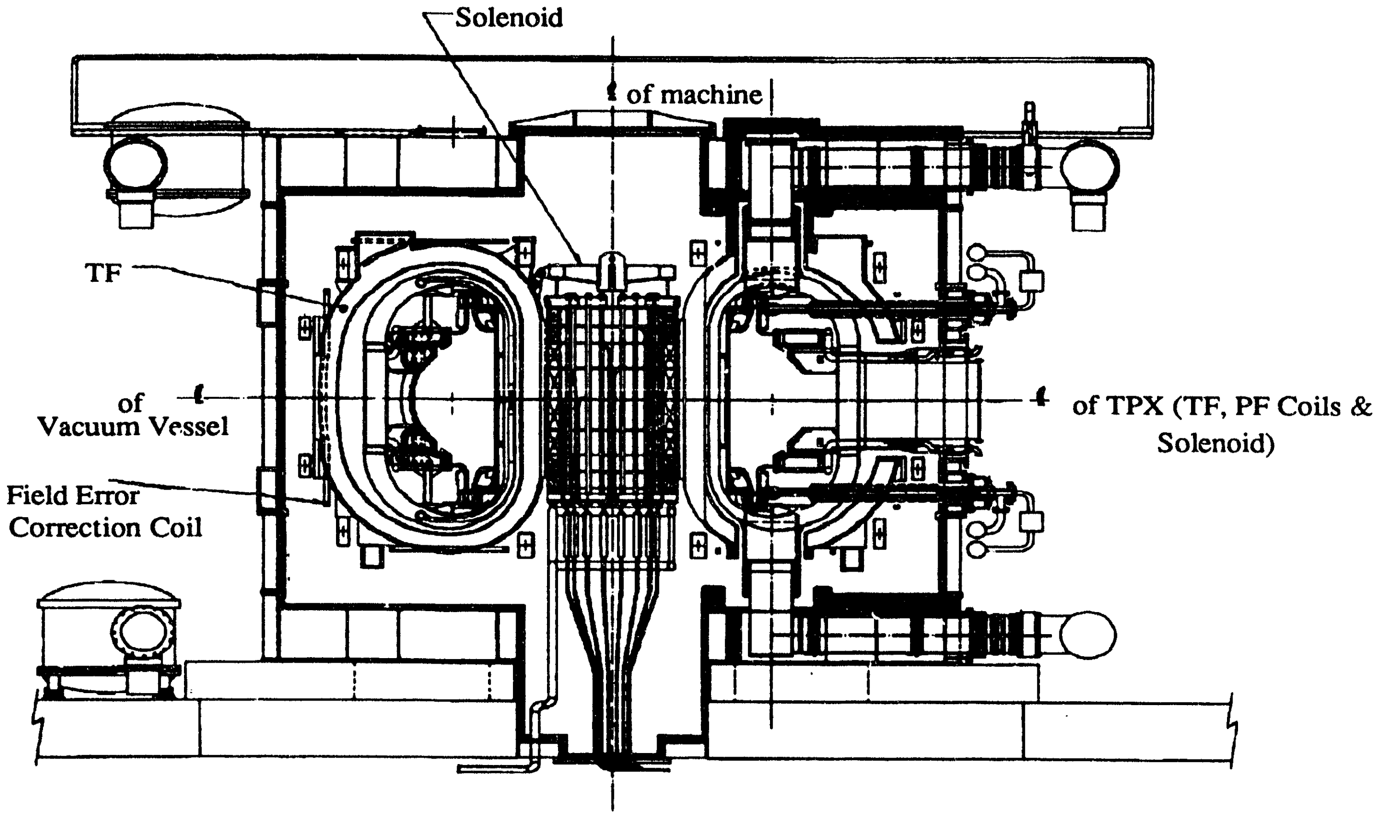


FIGURE 2. ELEVATION VIEW OF THE TPX CONFIGURATION

Large, passive conducting plates will be installed in the outer regions above and below the mid-plane and above and below the mid-plane on the inside toward the major axis. These plates will be electrically connected radially with conducting straps between horizontal ports. The vertical connecting straps accommodate current patterns that provide passive stabilization to plasma kink modes. An active coil system will be installed to provide vertical stabilization for displacements on time scales that are long

The double walled titanium vacuum vessel will be filled with borated water between shells to provide the shielding required by the magnets. The vessel can be baked and operated at elevated temperatures. The vacuum vessel and plasma facing components are discussed in detail in the accompanying paper by P. J. Heitzenroeder.

The toroidal field magnets will be wound with niobium tin cable inside a conduit. The inner leg of these coils will be wedged together to react the magnetic centering force. The poloidal field magnets will be wound with either niobium tin or niobium titanium cable inside a conduit, depending on their location and associated magnetic field environment. These coils will be cooled with supercritical helium. This magnet system is discussed in detail in the accompanying paper by D. D. Lang.

The heating and current drive system includes a combination of Neutral Beam, Ion Cyclotron and Lower Hybrid heating and current drive. The heating and current drive system is a design driver for the horizontal port configuration. This system is discussed in detail in the accompanying paper by D. W. Swain.

The TPX tokamak will be located in the TFTR test cell. During the design and fabrication of the TPX components the TFTR tokamak will be disassembled and removed. The power supplies that presently support TFTR operations will be reconfigured to power the TPX magnets and ancillary systems. The power systems for TPX are discussed in detail in the accompanying paper by C. L. Neumeyer.

## VI. SCHEDULE

A summary schedule for the TPX construction project is shown in Figure 3. As discussed previously the conceptual design for TPX has been completed and reviewed. The recommendations from the conceptual design review have been factored into the ongoing design process. At the beginning of FY 94 preliminary design (Title 1) commenced. After the completion of the final design for individual subsystems, the fabrication of major hardware will begin in FY 96. Installation of the hardware will begin in the TFTR test cell in about July 1998. First plasma will be accomplished in July 2000 after the assembly and testing of the hardware.

## VII. TECHNOLOGY BENEFITS

The primary role of TPX in the fusion program is related to the development of tokamak physics. However,

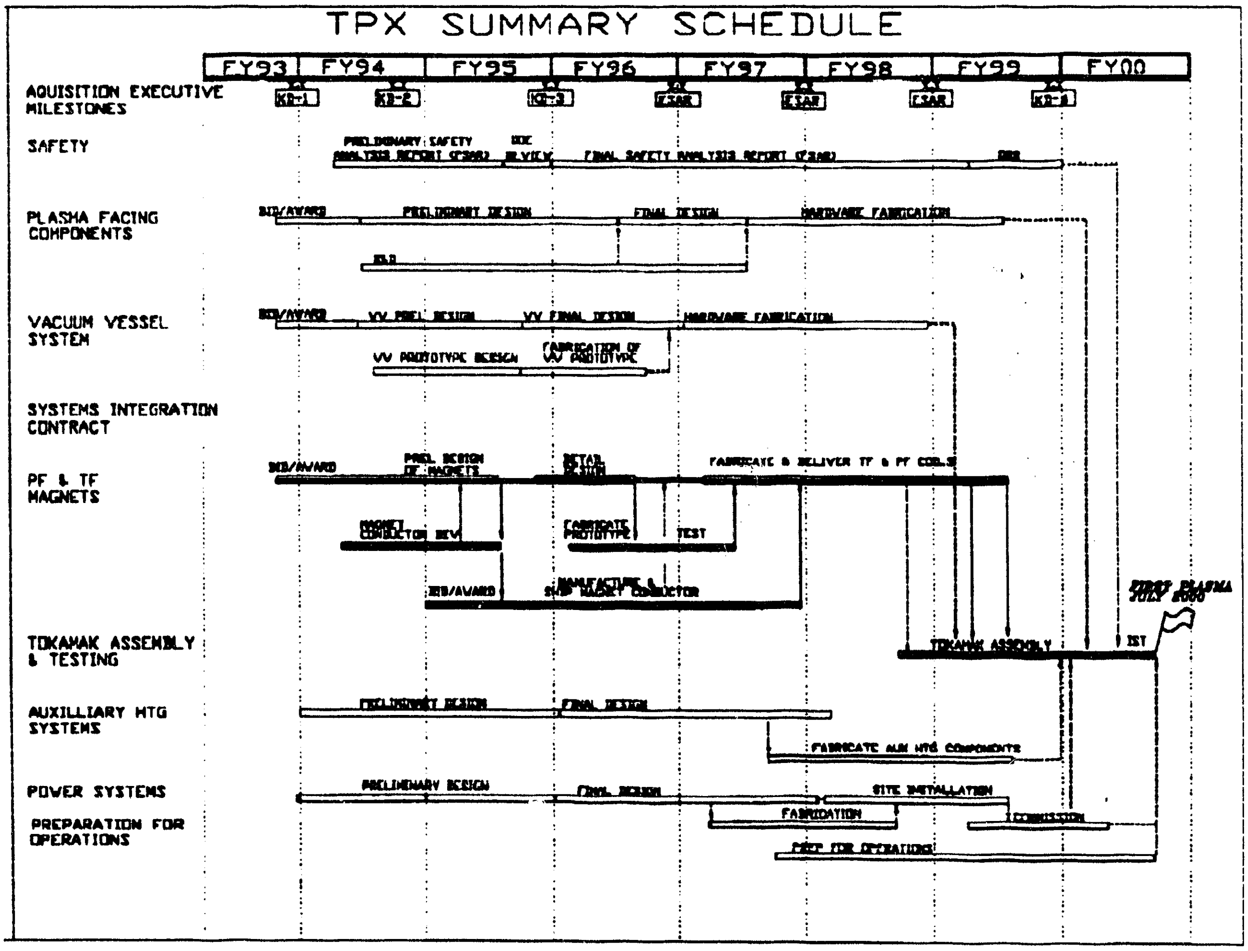


FIGURE 3. TPX SUMMARY SCHEDULE.

the TPX construction project on its way to providing an experimental facility will take significant steps in technology development. The most significant steps are in the areas of magnet, remote maintenance, and plasma facing component development.

The TPX magnet set will include for the first time a superconducting poloidal field coil set. The TPX parameters are set at levels that do not explicitly push the state of conductor development. However, the fact that the poloidal field magnet must accommodate the changing magnetic fields associated with plasma startup and disruptions will provide important magnet development.

While remote maintenance has been part of several large tokamak programs (e.g. TFTR and the Joint European Torus (JET)) no tokamak yet constructed, will accommodate full remote maintenance operation. The levels of activation in TPX will require that this issue be faced during the design and in doing so will provide a significant developmental step for the fusion program.

Successful TPX operation will require continuous cooling of much of the hardware internal to the vacuum vessel. The power density requirements exceed by a significant factor the levels of heat removal that has been realized in existing long pulse experiments. It is clear from ITER and future reactor designs that this is an important area of development for the fusion program.

## VIII. SUMMARY

A mission and supporting physics objectives have been developed, which establishes an important role for TPX in developing the physic basis for a future fusion reactor. The design of TPX include advanced physics features, such as shaping and profile control, along with the capability of operating for very long pulses. The development of the superconducting magnets, actively cooled internal hardware, and remote maintenance will be an important technology contribution to future fusion projects, such as ITER. The Conceptual Design and Management Systems for TPX have been developed and reviewed, and the project is beginning Preliminary Design. If adequately funded the construction project should be completed in the year 2000.

## ACKNOWLEDGMENT

This work supported by U.S. DOE Contract No. DE-AC02-76-CHO3073.

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