

Series No. 97-10

**KSTAR PROJECT EFFORTS IN THE  
UNITED STATES**

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This article is one in a series of occasional papers published by the Center for Science, Trade, and Technology Policy of George Mason University and the Science and Technology Policy Institute of Korea as part of their U.S.-Korea Science and Technology Cooperation Program. This article is drawn from Dr. Schmidt's presentation at the U.S.-Korea Forum on Fusion Science and Technology held on February 18-19, 1997 in Washington, D.C.

STEPI-GMU/CSTP Occasional Paper 97-10

The Tokamak Physics Experiment (TPX) was conceived to play the important program role of determining whether the tokamak approach could evolve smaller, less expensive, and more attractive fusion reactors than are forecast using conventional physics rules. TPX was being designed to extend advanced tokamak operating modes with high beta, confinement, and bootstrap current fraction to the steady-state regime. While the TPX was to be built primarily to explore advanced physics regimes in the steady state, doing so would have had the added benefit of expanding our tokamak technology base. Key technology developments would have been in the use of superconducting magnets, steady state power handling in the diverters, low activation material usage to allow access to in-vessel components during early phases of operation, and in remote maintenance techniques.

The TPX Project was canceled in 1995 due to overall budget reductions for the U.S. fusion program. However, the expertise gained and the technical data generated as part of the TPX design and R&D will be a valuable input to the Korean Superconducting Tokamak Advanced Research Project (KSTAR). The U.S. has organized a team of engineers and physicists to provide support to the KSTAR project, in part by providing a channel for conveying the knowledge base developed for TPX.

The engineering design strategy for TPX was to limit the required technology development and to employ conservative engineering design criteria. This design basis was consistent with the central role of this project in the U.S. fusion program and the associated need for an expeditious design and construction schedule.

The configuration and technology choices related to the TPX design were driven to a large extent by the requirement for long pulse, steady state operation. The choice of superconducting

that could be accommodated and the array of heating systems selected, derived from the advanced tokamak mission element. The requirement for TPX to operate with deuterium as a fuel resulted in a neutron fluence that had a strong influence on the configuration and maintenance. Also, the requirement to operate with deuterium was derived in part from the significant increase in plasma and neutral beam performance associated with this fuel. Shielding was required between the plasma and the TF coils to reduce the nuclear heating in the magnets and the associated refrigeration requirements. This shielding facilitated the use of hands-on maintenance outside the shield, although remote maintenance of hardware inside the vacuum vessel would have been required after the first few years of operation.

The TPX Project was to be a focused, national effort involving the coordinated response of a large part of Department of Energy's (DOE) fusion program. Although the Princeton Plasma Physics Laboratory (PPPL) was responsible for the project, the project included as participants many of the U.S. plasma physics research laboratories, universities, and industrial firms. In addition to the subsystems that were to be assigned to industry for design and industrial systems integration and construction management, essentially all of the fabrication would have been carried out by industry. The industrial involvement was to be through free and open competitive procurement.

The TPX Project had met the requirements of The National Environmental Protection Act, had its management systems in place and the Management Plan approved, was well into the preliminary design phase, and had completed much of the R&D required to validate the design. In September 1995, DOE notified the PPPL that the TPX Project was canceled and the Department directed the Laboratory to stop all TPX activity and to issue stop work orders to the contractors.

Over the last ten to fifteen years in the United States, we have developed a sizable team of engineers and physicists that have been working on a range of tokamak designs. As a result, scientists in the United States have developed the tools to manage these complex designs. We have developed the codes to support the engineering, and we have developed an understanding of the engineering design problems and how to address them. We have developed a range of R&D results that support

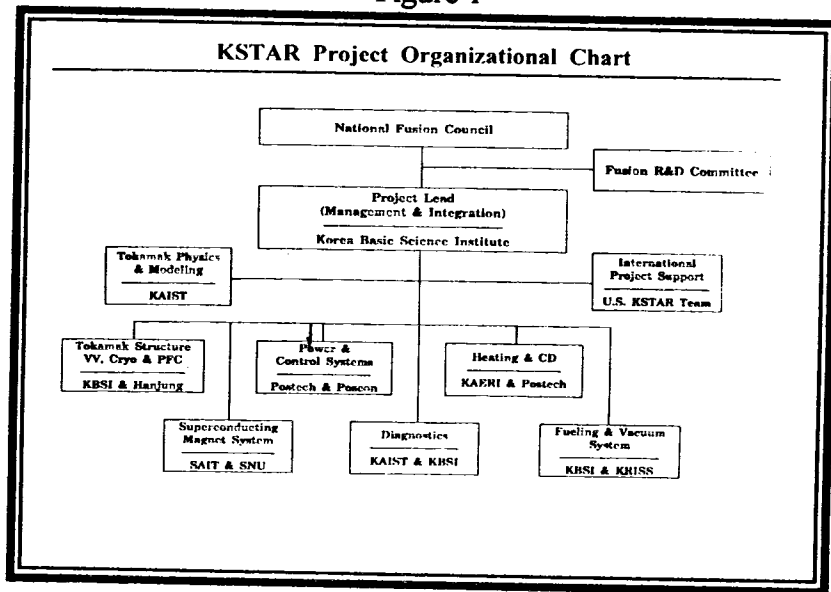
the design of superconducting tokamaks. This know-how is being applied to KSTAR. Since the physics community in the United States has not been funded to build a superconducting tokamak, we are excited about being involved in the KSTAR effort.

This article will address the management systems that have been developed in the United States, the physics and engineering codes, and some of the R&D results.

### Management Systems

Figure I show an organizational diagram of the KSTAR project. A national laboratory—the Korean Basic Science Institute—leads the project, with design physics and engineering distributed to other Korean institutions with expertise in the field. Involvement of universities brings both physics and high technology engineering knowledge to the project. There is considerable involvement of industry, from early in the design, through construction and commissioning of the machine. The complex organization is very similar to the organization that was developed for the TPX. In developing the TPX Project, we had solved the kinds problems that occur when managing this kind of complex and geographically diffuse activity.

Figure 1



## Systems Engineering

There are many issues that must be addressed by systems engineering. Techniques are necessary for establishing and controlling the requirements so that all parties know the design basis. Design integration is necessary to develop the design to meet the requirements. Of particular importance, is the configuration control necessary to see that all the diffuse organizational elements are developing their design in a controlled way that meets the project requirements. To minimize risk, you need to apply techniques for reviewing the design and feeding recommendations into the design process. Finally, you need techniques for overall engineering analysis so that all the various subsystems work together.

## Design Codes

A tokamak physics code for design purposes, called the Tokamak Simulation Code (TSC), has been developed. The purpose of this code is to produce a range of results to support the design process. For example, plasma current disruptions can be modeled to determine the loads from these disruptions to establish the hardware requirements. These codes can be used to analyze the evolution of the discharge.

Figure 2

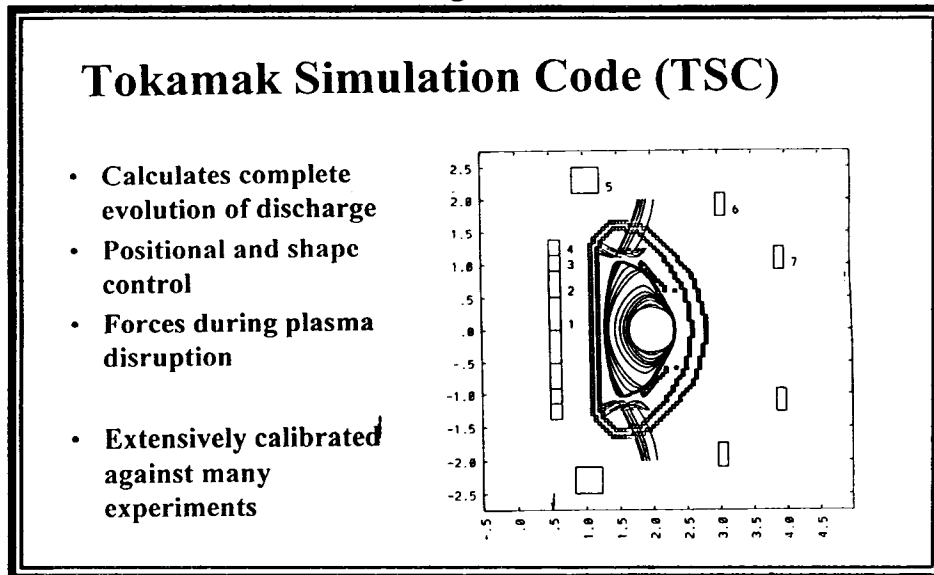
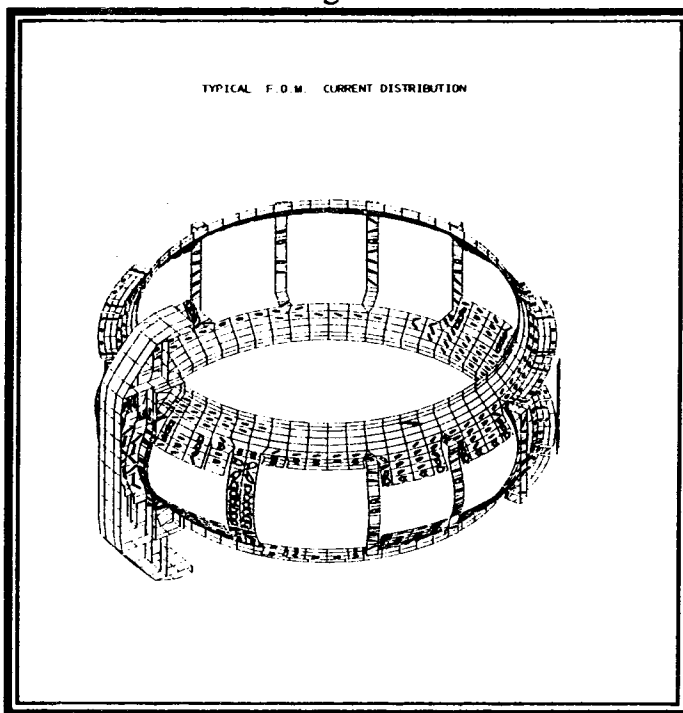


Figure 2 shows the results that have been produced by a Korean team using the TSC code to analyze the start up. It is easy to recognize the importance of these codes for determining the requirements of hardware, power supplies, and coil systems.

Figure 3 shows a diagram of TPX hardware near the discharge to help visualize the kind of stress analysis and electromagnetic analysis that is required. The figure shows the kind of TPX internal hardware which is presently being developed for KSTAR to control the plasma position. These configurations must be analyzed to determine the plasma induced current and associated stresses that lead to requirements for the engineering design. Figure 3 also shows the kind of results that are obtained. This simple case shows the currents developed

in the passive plates on the outside of the plasma during disruptions. These codes cross the currents with magnetic field to determine the forces that in turn establish the requirements for the design.

Figure 3



### Magnets and Antennas

During the TPX design, we carried out detailed stress and thermal analysis of the superconducting magnets. Figure 4 shows a section of the magnet including the insulation that surrounds the superconducting conduit. The conduit fits through the open slots. The kind of stress patterns that develop in the insulation when the coil is cooled down to room temperature can be seen. This analysis identifies relatively high stress in the insulation in the regions around the corners between the conduits. Stress at this level will lead to mechanical breakdowns in the insulation.

Figure 4

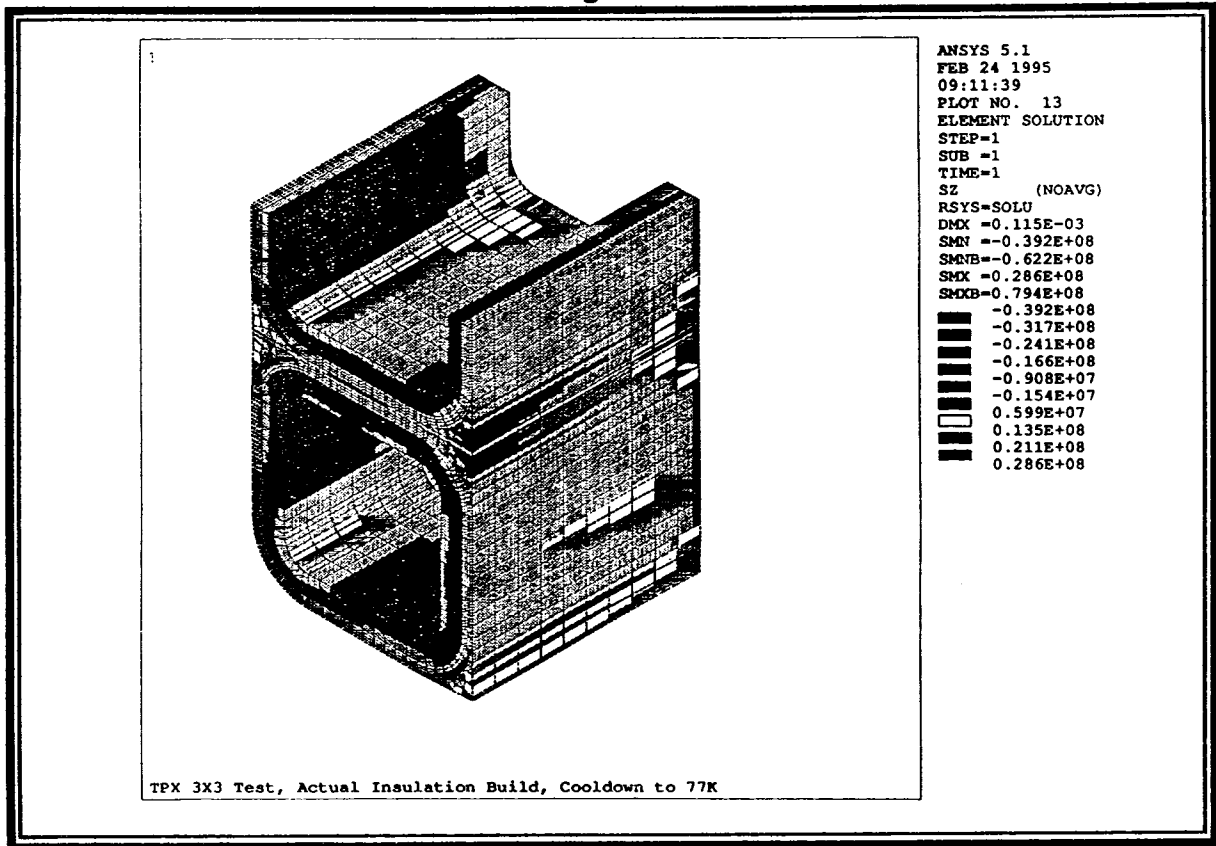
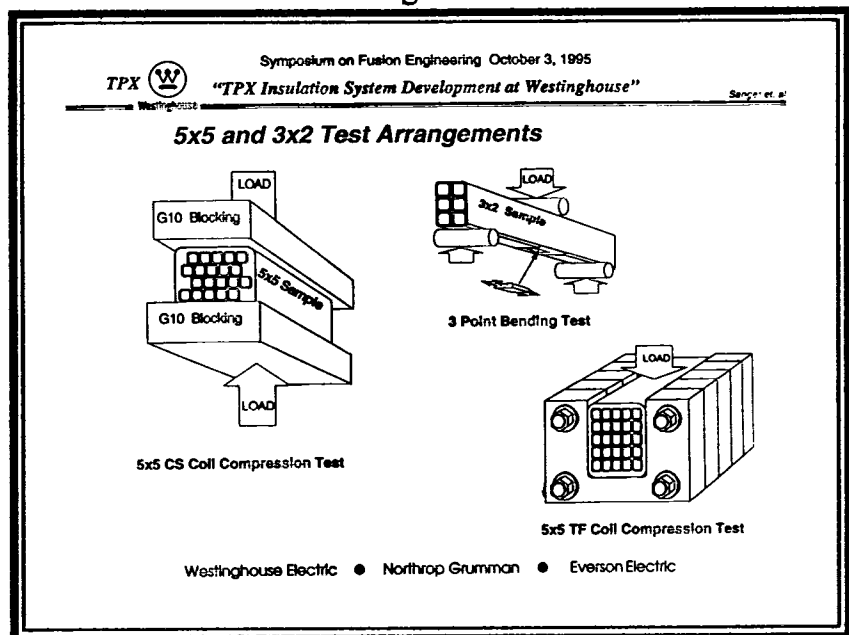


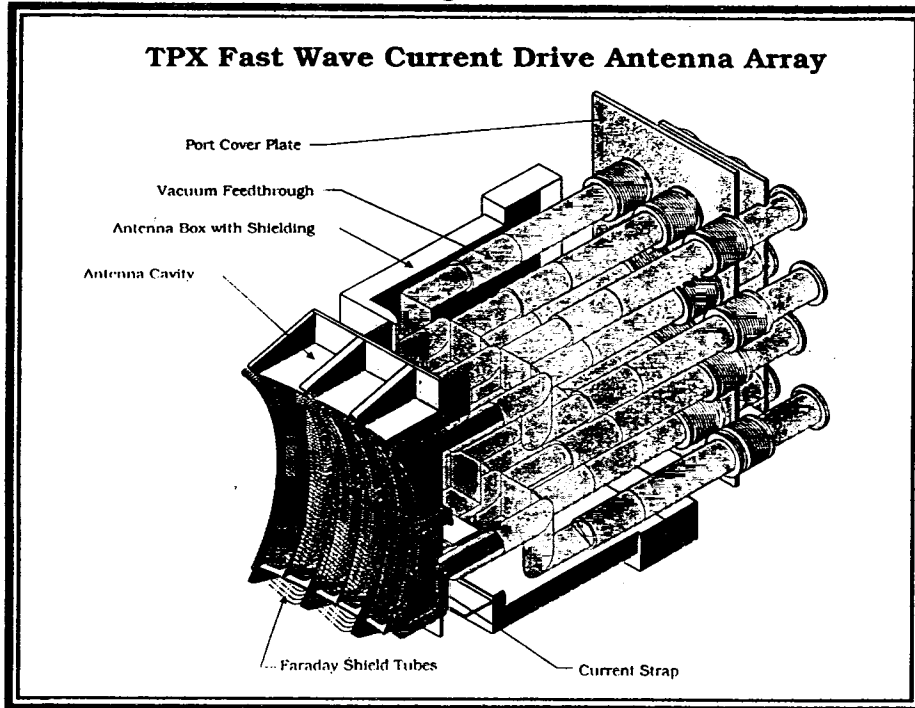
Figure 5

The TPX Project carried out significant R&D related to the magnets and the radio frequency (RF) antennas. After observing the stress problem described above, first in theory and then during tests, Westinghouse and Babcock & Wilcox—those companies responsible for the magnet system—planned and executed



a test program. Figure 5 shows cross-sections of conductors that were fabricated to test various insulation approaches. These samples were exposed to the range of stress patterns that are projected to exist in the actual magnets. Various insulation approaches were tested and one was selected that satisfied the design requirements.

Figure 6



Oak Ridge National Laboratory (ORNL) was responsible for the RF systems for TPX. Figure 6 shows an ICRF antenna. Included in this figure are straps that form the coupling elements, and the Faraday shield to protect the antenna and in turn shield the plasma from some of the

electro-static fields from the antenna. The Faraday shield is subject to high heat loads both coming through the antenna as electromagnetic power and also from the plasma as particle and radiant heat fluxes. We needed to assure ourselves that coatings were available that would withstand the heat loads. Figure 7 shows some of the results with B<sub>4</sub>C coating on a titanium Faraday shield. We used titanium in TPX because of the reduced activation during neutron bombardment. Figure 7 also shows the heating pattern during high heat flux tests of these coatings. Good results were obtained by using B<sub>4</sub>C to protect the Faraday shields.



## **Conclusion**

We have established a United States organization that is functioning well to assist the Koreans in their KSTAR efforts. At PPPL, we are responsible for a range of activities including management and integration of the project. The Massachusetts Institute of Technology is bringing their superconducting magnet expertise to bear by providing assistance on the magnets. General Atomics is sharing their knowledge of plasma-facing components' design and analysis and in-vessel diverter pumping. ORNL is involved in the RF antennas and design integration, cryostat, auxiliary heating and current drive, and torus vacuum pumping. Lawrence Livermore National Laboratory is focusing on physics, and power, and particle removal. Northrop-Grumman Corporation is helping with design integration. This team has been very active and has produced good results in support of the Korean program.