Title: Tokamak Physics Experiment (TPX) Cost and Performance Trade Studies Using Supercode

Author(s): Ronald L. Miller
J. D. Galambos
S. W. Haney
L. J. Perkins
J. Mandrekas

Submitted to: 15th IEEE/NPSS Symposium on Fusion Engineering
October 11-15, 1993 Hyannis, MA

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Tokamak Physics Experiment (TPX) Cost and Performance Trade Studies Using SUPERCODE †

R. L. Miller

Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA

J. D. Galambos

Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

S. W. Haney, L. J. Perkins

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

J. Mandrekas

Georgia Institute of Technology, Atlanta, GA 30332, USA

ABSTRACT

The Tokamak Physics Experiment (TPX) has been proposed to demonstrate steady-state operation and to develop advanced performance in terms of β and energy confinement. Major TPX cost drivers and the impact of physics and technology constraints and options on operating scenarios are identified. Key trade and sensitivity studies performed using SUPERCODE are summarized.

I. INTRODUCTION

The Tokamak Physics Experiment (TPX) is the next major proposed step in the U. S. magnetic fusion program [1-3]. To be sited at the Princeton Plasma Physics Laboratory (PPPL), TPX has the mission [4] to develop the scientific basis for an economic, compact, and steady-state tokamak fusion reactor, requiring the development and demonstration of stable, steady-state tokamak operating regimes with high β , high confinement, and high bootstrap-current fraction, consistent with ARIES recommendations [5]. The TPX engineering design incorporates superconducting magnets, actively cooled divertor and first-wall systems, and in-vessel remote maintenance. The deuterium plasma heating and current-drive systems include neutral beams, ICRH, and lower hybrid.

As part of the TPX conceptual design effort, the SUPERCODE [6], combining physics, engineering, and cost models, has been used to perform trade and optimization studies to establish the context of the reference design. Major TPX cost drivers and the impact of physics and technology constraints and options on operating scenarios are identified. Some results of key trade and sensitivity studies are described below.

†This work was supported by the U.S. Department of Energy at LANL under Contract No. W-7405-ENG-36 and ICO No. S-03563-A between PPPL and LANL, at ORNL under Contract No. DE-AC05-84OR21400, at LLNL under Contract No. W-7405-ENG-48, and at GIT under Contract No. DE-FG0590E52141.

II. COST MODEL

The TPX Work Breakdown Structure (WBS) defines and organizes the activities and subsystems which comprise the machine and associated projected costs. The Plant and Capital Equipment (PACE) direct cost is the sum of Hardware, Engineering, Installation, and Contingency costs. Operating Expenses (OPEX) include direct costs for Research and Development, Mockups, Conceptual Design, *etc.*. General & Administrative (G&A) PACE (9%) and OPEX (55%) indirect rates, representative of major US fusion laboratory experience, are applied to the direct costs to determine the total PACE and total OPEX costs, which then sum to yield the estimated Total Project Cost (TPC), about 510 M\$ (1993 US dollars). For each specific WBS item and cost category, cognizant engineers have recommended a cost algorithm based on the TPX conceptual design activity. Often the cost algorithms are specific to the PPPL site, because credit has been taken for use of the existing TFTR facilities. The reference cost model [7] has been maintained and updated as required at PPPL, and was the basis for the recent Independent Cost Estimation (ICE) cost review and validation. A derivative model, compatible with SUPERCODE, provides the opportunity to perform trade and sensitivity studies, using cost as an object function or constraint. The details of the SUPERCODE cost module are described elsewhere [8].

III. RESULTS

TPX parameters are taken to be linked by the Troyon relation, $\beta = \beta_N I_p / a B_T$, where I_p (MA) is the toroidal plasma current, B_T (T) is the on-axis toroidal magnetic field strength, and a (m) is the plasma half-width at the midplane. Two distinct operating scenarios follow from the TPX mission: Standard high-beta Tokamak (ST), consistent with the present tokamak data base at $\beta_N \simeq 0.035$ and $q_\psi \simeq 3.3$, and the Advanced-performance tokamak (AT), consistent with $\beta_N \simeq 0.05 - 0.07$ and

Fig. 1. A-\$ phase space for TPX illustrating contours of constant plasma current, I_p (MA), for the ST scenario.

an energy confinement time, τ_E , enhancement factor, $H \approx 3 - 4$, rather than 2 for the ST scenario.

Using SUPERCODE, key trade and sensitivity studies have been performed. A two-dimensional phase space of plasma aspect ratio, $A = R_T/a$, and device cost was selected to display the SUPERCODE results. In this A-\$ space, contours of selected device parameters (*e.g.*, plasma current, on-axis toroidal magnetic field strength, heating power, *etc.*) are displayed, as in Figs. 1,2. All design points in this phase space meet the usual constraints of the ST scenario; the density constraints were not applied. At each [A,\$] point the triple product, $n\tau_E T$, is maximized. TPX devices with $I_p \geq 2.0$ MA and $B_T \geq 3.0$ T imply 1992-\$ device costs greater than 450 M\$ and plasma aspect ratios in the range, $A = 4 - 5$. For fixed A , device cost is relatively insensitive to B_T , unless $B_T \geq 3.50$ T. Lower cost devices with reduced ST and AT performance are of marginal interest.

The capability for bi-modal optimization studies was added to SUPERCODE to allow the identification of TPX devices that meet the distinct requirements of both ST and AT scenarios. Modal variables/constraints (*e.g.*, n , T , I_p) are duplicated in each mode and treated separately. Synchronized variables (*e.g.*, R_T , TF-coil build) have the same value in all modes and are governed by synchronized constraints. Composite variables (*i.e.*, the largest, encompassing particular modal variables) are subject to mode-specific constraints. The multi-tasking capabilities of UNIX are invoked to clone copies of SUPERCODE to compute modal quantities.

Fig. 2. A-\$ phase space for TPX illustrating contours of constant magnetic-field strength, B_T (T), for the ST scenario.

The results of Fig. 3 are used to address the question: What is the least expensive machine that satisfies both the ST and AT missions? The on-axis toroidal magnetic field, B_T , is either fixed (synchronized) or varied, as indicated. Either the Day-1 or upgraded Day-n heating capabilities are invoked, as shown. The Day-n upgrade assumes 24 MW of both NBI and ICRH power. Device cost shows a minimum near $A \approx 4.5 - 5$ under all indicated assumptions. The minimum size device meeting both ST and AT requirements, occurs with plasma aspect ratio, $A \approx 4.5$, as indicated by Fig. 4. Here, the plasma geometric parameters are insensitive to whether the on-axis toroidal magnetic field, B_T , is treated as a fixed (synchronized) variable or not.

The required external heating powers depend on the value of plasma aspect ratio, $A = R_T/a$, and the choice of ST *versus* AT operating mode. The neutral-beam heating power as a function of plasma aspect ratio is shown in Fig. 5; the curves for AT mode (denoted by squares and triangles) are nearly coincident. Fig. 6 shows ICRH heating power under the same conditions. Total auxiliary heating power is minimized for $A \approx 4.5 - 5$. The Day-1 constraints on heating power preclude high-current, low-A devices.

These sample SUPERCODE results point to the selection of TPX parameters that maximize performance in both ST and AT operating modes while minimizing device cost. Major parameters of the TPX conceptual design are summarized in Table I.

Fig. 3. TPX device cost (M\$) as a function of plasma aspect ratio, $A = R_T/a$, assuming fixed (synchronized) or varied on-axis magnetic field, B_T , and either Day-1 (NBI: 8 MW, ICRH: 8 MW) or Day-n (NBI: 24 MW, ICRH: 24 MW) heating.

Fig. 4. TPX major toroidal radius, R_T (m), and minor plasma radius, a (m), as functions of the plasma aspect ratio, $A = R_T/a$, assuming fixed (synchronized) or varied on-axis magnetic field, B_T . The choice $A \simeq 4.5$, near the center of a shallow minimum of R_T , tends to minimize the size of the device. Use of B_T as a fixed variable is not decisive in the choice of these plasma geometrical parameters.

Fig. 5. TPX neutral-beam heating power (MW) as a function of plasma aspect ratio, $A = R_T/a$, assuming fixed (synchronized) or varied on-axis magnetic field, B_T , between ST and AT operating modes. Day-1 constraints on NBI and ICRH power lead to the choice of $A \geq 4.5$. The AT-mode curves, denoted by squares and triangles, are nearly coincident.

Fig. 6. TPX ICRH heating power (MW) as a function of plasma ratio, $A = R_T/a$, assuming fixed (synchronized) or varied on-axis magnetic field, B_T , between ST and AT operating modes. Day-1 constraints on NBI and ICRH power lead to the choice of $A \simeq 4 - 5$.

TABLE I
Summary of TPX Parameters

PARAMETER	VALUE
Plasma aspect ratio, $A = R_T/a$	4.5
Major toroidal radius, R_T (m)	2.25
Minor plasma radius, a (m)	0.50
Plasma vertical elongation, κ_x	1.6-2.0
Toroidal magnetic field, B_T (T)	4.0
Plasma current, I_p (MA)	2.0
Day-1 Heating and Current Drive:	
NBI (MW)	8.0
ICRH (MW)	8.0
LH (MW)	1.5
ST-mode $\beta = \beta_N I_p / a B_T$	0.035

The cost of new ICRH heating capability dominates the upgrade of existing TFTR NBI units in WBS-2 and the cost of the superconducting Toroidal-Field (TF) coil set dominates WBS-1. Table II summarizes baseline PACE and OPEX costs for TPX according to the higher-level WBS items. The total device cost in 1992-dollars is 453.1 M\$. Due to present space limitations, cost details at the lower WBS levels and the constituents of the PACE and OPEX costs are reported elsewhere [8].

TABLE II
Sample SUPERCODE TPX Cost Summary^(a)

WBS ITEM	PACE	OPEX
1 Tokamak Systems	179.4	19.2
11 Plasma Facing Components	35.0	3.8
12 Vacuum Vessel	25.4	2.2
13 Toroidal-Field (TF) System	56.6	9.2
14 Poloidal-Field (PF) System	26.0	2.4
15 Cryostat	10.5	0.9
16 Tokamak Support Structure	2.5	0.3
17 Assembly & Test	17.7	0
18 Tokamak Shielding	5.7	0.5
2 Auxiliary Heating & CD	96.2	2.1
21 NBI	31.0	0.9
23 ICRH	65.1	1.1
24 LH	0	0
3 Fueling & Vacuum Systems	10.0	0.7
4 Power Systems	28.0	0.5
5 Maintenance Systems	16.7	8.2
6 Data Systems	27.4	1.4
61 Central I&C	10.6	0.4
61 Plasma Diagnostics	16.8	1.0
7 Facilities	19.5	0.2
8 Preparations for Operations	0	10.4
9 Project Support	21.3	12.0
Total Device Cost	398.4	54.7

^(a) 1992 dollars.

IV. SUMMARY

The success of TPX improves the fusion-power-plant relevance of the tokamak. Equipped with a detailed cost module, SUPERCODE has been applied to the conceptual design and optimization of the TPX. Key trade and sensitivity studies have been performed, confirming a fairly robust TPX conceptual design at $A \simeq 4.5$. Minimizing projected cost while maximizing performance has been a driving consideration. Operational flexibility is addressed by bi-modal (ST and AT) optimization of device parameters. The demonstrated capability for bi-modal optimization establishes the techniques for future multi-modal optimizations. Use of the SUPERCODE for TPX studies diminishes as the TPX moves into the engineering design phase. The code package developed in this work is being adapted for future studies of demonstration (DEMO) tokamak power plants and other devices.

ACKNOWLEDGEMENT

The authors acknowledge the assistance of R. T. Simmons (PPPL) in the ongoing provision of current TPX cost baselines and useful discussions with R. J. Goldston (PPPL), G. H. Neilson (ORNL), W. M. Nevins (LLNL), and W. T. Reiersen (PPPL).

REFERENCES

- [1] G. H. Neilson *et al.*, "Physics Design Requirements for the Tokamak Physics Experiment (TPX)," these Proceedings.
- [2] W. T. Reiersen, "The Engineering Design of TPX," these Proceedings.
- [3] G. H. Neilson *et al.*, "Design of a Superconducting Steady State Advanced Tokamak," Proc. 17th Symp. on Fusion Technology, 1992, 2, 1636 (1993).
- [4] R. J. Goldston *et al.*, "The Mission and Physics Design of TPX," Princeton Plasma Physics Laboratory report PPPL-CFP-2821 (1993).
- [5] F. Najmabadi *et al.*, "The ARIES-II and -IV Second Stability Tokamak Reactors," University of California Los Angeles report UCLA-PPG-1461 (to be published).
- [6] S. W. Haney *et al.*, "A 'SUPERCODE' for Systems Analysis of Tokamak Experiments and Reactors," *Fusion Technology* 21, 1749 (May 1992).
- [7] R. T. Simmons, "TPX Cost/Schedule Overview," TPX Conceptual Design Review (March 29 - April 1, 1993).
- [8] R. L. Miller, "Fusion-Device Costing Module for Use in SUPERCODE," Los Alamos National Laboratory document (to be published, 1993).

**DATE
FILMED**

12 / 27 / 93

END