



Department of Energy  
Germantown, MD 20874

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~~MEMORANDUM~~ FOR DISTRIBUTION

FROM:

*NAD*  
N. Anne Davies  
Associate Director for Fusion Energy

SUBJECT:

Technical and Cost Assessment of the "PCAST  
Machine"

Attached for your information is the Executive Summary of the subject report which describes the results of a modest three-month design study commissioned by DOE in response to the July 1995 Fusion Review Panel Report of the President's Committee of Advisors on Science and Technology (PCAST). The report assesses the technical feasibility and cost of an ignition and moderate-pulse burn experiment. This mission is a physics subset of the International Thermonuclear Experimental Reactor's (ITER) broader mission, and was identified by the PCAST Panel as a means to offer a significantly lower cost next step in fusion energy development.

The report concludes that for the more limited mission, an attractive ignition and moderate-pulse burn experiment can be built using copper magnets.

It must be understood, however, that this "PCAST Machine" alone does not provide the full set of scientific and engineering capabilities to be provided by ITER, such as very long pulses, superconducting magnets, and nuclear technology development. In carrying out this study, the Department's intention was to provide an evaluation of the PCAST recommendation and not diminish our support for the ITER Engineering Design Activities.

Copies of the entire report will soon be available through the Princeton Plasma Physics Laboratory (Contact: Dr. John Schmidt at 609-243-2538).

Attachment

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**Technical and Cost Assessment of the "PCAST Machine"**

**Prepared by the  
PCAST Study Group**

**Executive Summary**

**November 30, 1995**

## **Approach to the Study:**

The Office of Fusion Energy requested that a three month study be undertaken to assess the recommendations made by PCAST for a reduced scope ITER mission. The PCAST suggested that a device with a reduced mission of ignition and burn control studies for moderate pulse lengths could address the physics of burning plasmas at lesser cost than the present ITER mission. If such a machine were to have a substantially reduced cost relative to ITER, PCAST reasoned that full partnership by the US might be feasible under present flat budget projections.

The study was chartered to develop a design to meet the reduced mission and compare its construction cost with ITER. In addition the study explored the cost and performance sensitivity to variations in design approach and physics performance. To better understand the cost of such a project in US terms, the design example was also to be estimated in a Total Project Cost format.

The groundrules established for the study included the use of "ITER Physics" and the desire to scale costs from "ITER estimates" whenever possible.

The study has been carried out by a team drawn from GA, MIT, LLNL, ORNL and PPPL, and has been funded at the 2.5 Professional Man Year level. The study is documented as a stand-alone Executive Summary, and as a Final Report.

## **Mission and Role of the PCAST Machine**

The Scientific Mission of the "PCAST Machine" is to explore the physics of ignition and burn control in a DT tokamak plasma on shorter time scales than those for ITER, and therefore represents a sub-set of the ITER mission. The more limited mission omits any specific requirements for nuclear fluence, and the engineering qualification of prototypical reactor subsystems.

We have taken a 120 second burn time ( $I_p$  flat-top of 135 sec) for the design example, on the basis that it provides sufficient time to explore burn dynamics where helium accumulation and exhaust are critical issues. We recognize that substantially longer burn times would be required to reach a fully equilibrated current profile, or to

fully explore performance optimization by current profile control, but find such a requirement incompatible with the spirit of the reduced cost targets sought by PCAST.

### PCAST Machine Design Example

#### *Configuration:*

It is traditional to approach a study of this nature by performing trade-off studies using a systems code approach, and to select an optimized baseline design based on these results. The time limitation for this study, however, required that a parallel approach be taken in which a "design example" was chosen at the start, allowing more detailed engineering and costing to proceed in parallel with the systems code work. The systems code results could then be used to illustrate the performance and cost sensitivity to perturbations around the chosen example. These perturbations include optimization of the design point (for example, changes in aspect ratio or TF/CS envelope trade-offs), changes in burn time, and changes in the choice of cost scaling factors.

The parameters for the 5.0 meter major radius design example selected are listed in Table 1.0, together with ITER parameters.

| Table 1.0: Design Example      | ITER     | PCAST |
|--------------------------------|----------|-------|
| Toroidal Field (T)             | 5.7      | 7.0   |
| Elongation (k95)               | 1.6      | 1.75  |
| Triangularity (delta95)        | 0.24     | 0.45  |
| Plasma Current (MA)            | 21.0     | 15.3  |
| Major Radius (m)               | 8.14     | 5.00  |
| Minor Radius (m)               | 2.8      | 1.5   |
| Fusion Power (MW)              | 1,500    | 400   |
| TauE/Tau ITER93H-ELM-free      | 0.77     | 0.77  |
| Beta Normal (%-m-T/MA)         | 2.3      | 1.6   |
| Fraction of Greenwald Limit    | 1.6      | 0.8   |
| TauE (sec)                     | 5.1      | 4.4   |
| Helium confinement time (sec)  | 51       | 44    |
| Tau-skin [Mikkelsen,91] (sec)  | 323      | 105   |
| Burn time (sec)                | 1000     | 120   |
| Installed Auxiliary Power (MW) | 100      | 60    |
| Number of Pulses               | 12,000 * | 5,000 |

\* Basic Performance Phase

The machine configuration chosen for the design example is shown in Figure 1.0, and is compared with ITER in Figure 2.0. All coils use copper conductors cooled to cryogenic temperature. The TF coils are cased, and are bucked against the Central Solenoid. The basic support structures are patterned after ITER, with upper and lower crowns and intercoil structures between the outer legs supporting the out-of-plane loads.

The PCAST Machine utilizes stronger shaping than the ITER machine to increase the plasma current capacity at a 5.0 meter radius. The value chosen would still be considered relatively moderate, and as it lies within the existing database, we considered it to meet the spirit of "ITER Physics" rules. In our initial scoping studies, we noted that shaping offered the highest potential for reduction in machine size of any of the variables studied.

We recognized that strong shaping can have a negative impact on the cost of out-of-plane structures, design requirements for the central solenoid and control power (and cryogenic refrigeration in the case of superconducting coils.) We believe, however, that certain aspects of the PCAST Machine make it less vulnerable to these negatives. We have found, for example, that the radial build of the TF magnet configured to meet the PCAST burn time of 120 seconds can accommodate more out-of-plane loads than the comparable thickness, but much taller ITER TF magnet. In addition the reduced neutron fluence of the PCAST device relative to ITER leaves available the option of installing control coils inside the vacuum vessel to control highly shaped plasmas. The vacuum vessel is also fitted closely to the plasma on the outboard side, providing the passive stabilization needed to control the vertical instability.

The plasma configuration utilizes a double null divertor, with a "long vee" shape similar to ITER. Projected heat loads are in the range of 4-6 MW/m<sup>2</sup>, requiring no special heat reduction techniques in the divertor.

### *Physics Considerations:*

The PCAST Machine design example has been chosen to provide high confidence of achieving its scientific mission. The so-called "ignition margin,"  $M_{ig} \equiv P_{\alpha}/P_{loss}$ , is chosen to be identical to that of ITER under equivalent assumptions about profile shapes, impurity concentrations, and confinement scaling. The PCAST Machine design point reduces some of the uncertainties which are present for ITER.

- 1) The PCAST Machine operates below the Greenwald density limit. While the physical basis for the Greenwald density limit has not yet been clearly established, it provides an empirical upper bound to the density range that can be accessed in high-performance H-mode plasmas in the absence of deeply penetrating pellets.
- 2) The PCAST Machine operates well below the Troyon beta limit.
- 3) The PCAST Machine operates in a regime of divertor physics parameters where familiar "high recycling" physics provides sufficient heat dispersal for successful ignition and burn control studies. This does not preclude operation with a so-called "detached" divertor, but makes such operation a topic of study rather than a requirement for success.
- 4) The PCAST Machine is equipped with sufficient auxiliary heating power to assure access to the H-mode at moderate plasma density. There is also sufficient auxiliary heating power to permit qualification of all divertor surfaces to their full anticipated heat loads (and beyond) in hydrogen before introducing deuterium and tritium.

In addition to its stable, ignited burn point, the PCAST machine is capable of exploring a number of different operating scenarios. If  $M_{ig}$  proves to be lower than presently anticipated, auxiliary drive power is provided for operation at full fusion power with  $Q$  as low as 6.7. On the other hand, if the scaling of  $M_{ig}$  is favorable, the toroidal field and plasma current can be reduced, and the pulse length extended.

If "Advanced Tokamak" confinement is achieved (e.g. 1.5 x ITER93H) then it may be possible to reduce the toroidal field and current (e.g. to 4 – 5T) and explore high-Q current-driven operation in DT plasmas for pulse lengths greater than the current profile relaxation time. Strong plasma shaping and fast position control are provided, as would be needed for Steady-State Advanced Tokamak operation. Sufficient space is also provided to optimize the divertor configuration. Current-drive and current profile control capabilities would have to be installed as upgrades to the basic device, but adequate port space is available.

*Engineering Considerations:*

Typical engineering parameters for the PCAST machine magnetic systems are given in Table 2.0.

| <b>Table 2.0: Typical Engineering Parameters</b> |      |
|--|------|
| Number of TF Coils                               | 16   |
| TF Stored Energy (GJ)                            | 33   |
| TF Ramp Time (s)                                 | 150  |
| TF Flat Time (s)                                 | 165  |
| Maximum Grid Power (MW)                          | 650  |
| Number of 120 s Burn Pulses per 24 hour          | 5    |
| Refrigeration Plant Capacity @ 80 K (MW)         | 8.2  |
| Refrigeration Plant Capacity @ 30 K (MW)         | 0.08 |
| Refrigeration Steady Input Power (MW)            | 80   |

One of the major differences from ITER which accrues from the PCAST Machine mission, is the greatly reduced fluence, which in turn reduces the shielding requirements. The 25 cm shielding in the PCAST machine is incorporated into the vacuum vessel, and is chosen to limit the fluence from the five thousand, 120 second pulses, to a level which meets the ITER requirements for organic insulation. The fluence in the PCAST Machine is of a magnitude to require full remote maintenance.

The shaping requirements for the PCAST Machine place increased demands on the Central Solenoid and on the out-of-plane support of the TF coil. The solenoid must be segmented, and the center module driven at high currents relative to the other modules. In addition, the fringe field from the modules results in a concentration of out-of-

plane load in the center leg region relative to ITER. Fortunately, the relative thickness of the TF coil in the PCAST Machine is much greater than in ITER, and the stiffness of the inner leg is sufficient to withstand the increased loads.

The vertical separating force on the TF is taken in tension in the conductor and case, and the centering force is reacted by bucking against the CS. In our design example, the inplane stresses proved to be acceptable for a static stress, but to have more limited margin with respect to fatigue.

The Central Solenoid stress levels, which are reduced by the bucking action of the TF, are similar to those in the TF.

The vacuum vessel stress levels resulting from plasma disruptions will be a major challenge in the PCAST machine as they are in ITER. The vacuum vessel thickness has been scaled appropriately from BPX to account for the disruption loads. A cost factor was also added to the first wall and divertor elements to reflect the uncertainty associated with additional supports needed for asymmetric halo currents.

One of the dominant engineering considerations for cryogenically cooled copper coils of this scale, is the magnitude of the cryogenic system. The largest modules currently produced in industry for air liquefaction plants are of 500 ton per day (1 MW) capacity, and would probably be paralleled to achieve the PCAST required 8.2 MW capacity for re-liquefaction of nitrogen. The PCAST Machine requirement would be equivalent to a plant which would produce 4,100 tonnes per day of liquid nitrogen, and would be approximately two and a half times larger than the largest currently operating US plant.

Operation of a plant of this scale would be of concern if the cryogenic gasses boiled off during the pulse were released rather than being re-liquefied. With the cooling strategy we have selected, the cryogenic fluid is used only for pre-cooling and not for active heat removal during the pulse; the gas can therefore be continuously re-liquefied. Environmental and safety impacts are substantially reduced, as re-liquefying the gas is a much more benign process, and large volumes of cryogenic liquid do not have to be transported or stored.

A cryogenic system trade-off can be made against both the method of cooling, and the starting temperature. If the coils are only pre-cooled and warm up during the pulse, the copper resistivity rises throughout the pulse, and more dissipation results than if the temperature were held constant by active cooling. The less energy dissipated, the less the required capacity of the refrigeration plant. The trade-off, however, is the attendant complexity and space requirements for coolant passages and manifolds to circulate the large volumes of coolant required for active cooling.

The lower the starting temperature, the less energy is dissipated (thereby reducing power supply costs), whether inertial or steady cooling. The trade-off in this case is that the refrigeration is more costly at lower temperature, and a determination must be made if a net cost gain can be realized.

These various trade-offs have been considered in this study. We reach the conclusion that the simplicity of pre-cooling rather than steady cooling is preferred, and that a starting temperature of 80 K results in lower overall costs. Precooling to 80 K is provided by the liquid nitrogen system, in conjunction with a primary cooling loop that uses helium gas. In our design example, however, it proved necessary to pre-cool the center module of the CS (PF1) to 30 K to reach the 120 s burn-time goal. Pre-cooling below 80 K is provided by a helium gas refrigerator that cools down to 30 K.

### **Trade-Off Considerations:**

Trade-off studies have been carried out to illustrate variations in parameters around the design example. Results show the sensitivity of physics and engineering performance and relative cost to changes in aspect ratio, major radius, plasma shaping, wall loading and burn time. The sensitivity to aspect ratio is quite flat. The sensitivity to shaping, especially when coupled to wall loading, is strong.

The studies do not indicate a strong cost dependence around the PCAST point for modest changes in the burn time. In this range, an increase of 100 seconds in burn time increases the major radius and cost by about 5 %.

On the other hand, more pronounced reductions in burn time, for example to include the 10 second BPX design point, would allow changes in the technical approach (higher field and BeCu alloy

conductors), and would lead to much larger cost reductions. The BPX construction cost, for example, is projected to be about one third that of the PCAST machine.

Formal trade-offs have not been made on several of the engineering choices, which were based more on judgment and expediency. The choice of a bucked ITER-like configuration provides a case in point, where several alternate approaches were considered at a conceptual level. A wedged configuration BeCu alloy conductor coil scaled from BPX, and a sliding joint/external support structure configuration, scaled from Alcator C-Mod were both studied. In the case of the BPX scale up, the dissipative power appeared intractably high. In the case of the C-Mod scale up, the performance appeared comparable with the ITER-like bucked configuration, but carried the uncertainty of the sliding joint approach. The ITER-like configuration was chosen because it provided a satisfactory design point, and allowed us to scale components from a well defined design concept.

#### **Cost Considerations:**

The estimated cost of the PCAST Machine has been derived by scaling components and systems from ITER costs, or from other design projects like BPX or TPX when judged to be more applicable.

Cost scaling, as opposed to a "bottoms up" estimating approach involves considerable judgment, and the choices made are debatable. We have used our best judgement of these factors to determine an estimated cost of the PCAST machine, and then used some of the alternate scaling factors to estimate the uncertainty range.

We find that the estimated construction cost of the design example to be approximately 2.6 B\$ (1989 \$s), which is 44% of the 5.850 B\$ estimated construction cost of ITER.

The estimated Total Project Cost for the PCAST machine (using US formalism) would be 5.8 B\$ in 1995 dollars.

We estimate that the range of uncertainty in the construction estimate resulting from our scaling choices for the various WBS elements, to be approximately -5 % to +15 %.

There is also the uncertainty of cost associated with future design development. Reduced costs may result from design optimization; on the other hand, increased costs may arise from a need for design compromises. Both considerations are clearly a major factor in the PCAST Machine where there has been relatively little time for design development.

Given these various uncertainties, we believe it is most appropriate to describe the construction estimate for the PCAST machine as *"approximately 50 % of the cost of ITER, with a range of 40 to 60 %."*

### **Future Studies: Potential Role of the PCAST Machine**

Should further studies be undertaken, we suggest that the following points be taken into consideration:

- (1) Machines of this scale require international agreement and shared resources, and therefore future studies should be undertaken in that context.
- (2) This study has shown that the optimal configuration for ignition devices can be determined on the basis of mission requirements, design constraints and cost. Long (1000s) burn time and high fluence missions appear to favor superconducting devices. Adiabatic, copper coil devices appear better suited for missions requiring only intermediate (100s) burn times. High strength copper alloy devices such as BPX appear better suited for short (10s) burn time applications.
- (3) This study has shown that the cost of intermediate (100s) burn time machines cost approximately three times as much as a minimum burn time (10 second) driven device ( $Q > 5$ ) such as BPX. Future studies might address the cost/benefit tradeoff in considering such a minimum scale machine, which could also serve as a vehicle to explore advanced operating modes on a transient basis.
- (4) Future studies should examine the additional benefits that could result from more advanced physics "rules" should they materialize. For example, there has been significant progress in the exploration of regimes (e.g., the PEP mode, VH-Mode, and Enhanced Reversed-Shear mode) where the energy confinement is enhanced by as much as a

factor of 2 over H-mode scaling predictions. By designing a burning-plasma machine to take advantage of these physics improvements, further cost reductions might be realized.

(5) Future studies should address what role a moderate or short burn copper machine might be expected to play in the overall world fusion strategy.

The PCAST Machine was envisioned by the PCAST Committee as one element in an international ITER Program, composed of (i) a high-intensity 14 MeV neutron source for materials testing; (ii) the PCAST Machine itself, with the scientific mission to explore the physics of ignition and burn control in a DT plasma; and (iii) a DD steady-state advanced tokamak to provide experience with superconducting technology and steady-state operation. The PCAST Committee believed that the combination of these three devices might be less expensive than the ITER machine itself, and would provide the necessary scientific and technological basis for proceeding with the development of fusion power.

We have not addressed such issues in this study. We have endeavored only to better define and cost the PCAST suggestion for a moderate burn time ignition device, with a more limited mission than ITER.

## **Attachment 1: Index to the Full Report**

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\* Principal Editors/Authors of Chapters

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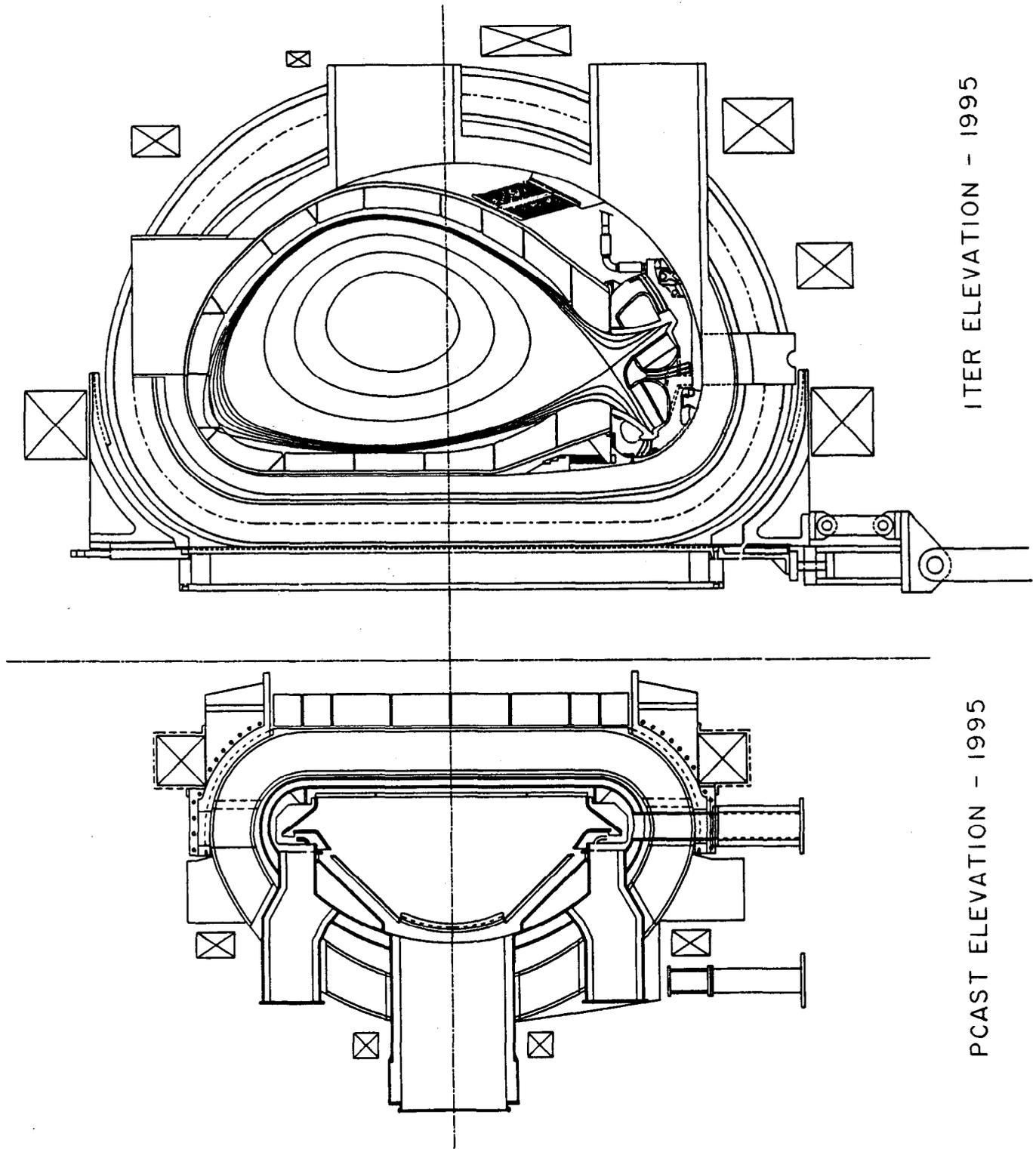


Figure 2