FUSION POWER DEVELOPMENT PATHWAYS

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INTRODUCTION

During the national fusion program Technical Planning Activity (TPA) led by Argonne National Laboratory (1,2), it was proposed that a systematic activity be initiated called Development Pathways Analysis. This activity was defined as "developing and applying methodologies for assessing the cost, risk, and schedule impacts of differing approaches to fusion development." The TPA report states that an "important objective is to identify pathways that lead to useful commercial products while minimizing development times and costs." The report also states that the "methodologies incorporate such factors as technical uncertainties and the size, cost and number of needed test facilities."

No such systematic activity has been implemented as part of the fusion program management to date. Instead, what has been adopted (for example, as part of the DOE National Energy Strategy) is what the TPA report referred to as a "reference scenario." This reference scenario describes a single "pathway" to fusion power commercial application as a central station electric power plant. Within that single "top level" pathway, there are of course multiple "lower level" pathways to accomplish the technical objectives of each program subelement. Consideration of such multiple technical pathways are a routine part of the ongoing R&D programs and are not the subject of the present report. An example of such a subelement multiple pathways analysis is the process of choosing materials for the ITER blanket.

In this report, we will consider the national reference scenario development pathway to fusion power and will comment on several variations that could be analyzed as part of a development pathways analysis activity.

THE REFERENCE SCENARIO

Shown in Figure 1 is the top level national reference scenario development pathway to fusion power, according to the U.S. Department of Energy (3). It consists of seven program elements: Tokamak Fusion Test Reactor, Tokamak Physics Experiment, ITER, Materials Test Facility, Blanket Test Facility, Demonstration Power Plant, and Core Program. Three of these (ITER, Materials Test Facility, and Blanket Test Facility) are grouped as "International Programs," by which is meant that planning, design and construction of these facilities is envisaged to be accomplished jointly with other countries. One of those facilities (Blanket Test Facility) appears as a dashed box, meaning that its need has not yet been formally acknowledged, either nationally or internationally.

The role, objectives, and technical characteristics of these facilities have been described in a variety of program documents and are frequently rephrased or revised slightly. An abbreviated summary follows.

The Tokamak Fusion Test Reactor (and similar non-U.S. devices JET and JT-60) provides a test of tokamak plasma confinement physics at conditions of temperature and density similar to what is required to achieve "scientific energy breakeven" for short (few second) pulses. It also has begun tests of the effects of adding tritium to the plasma mixture in expectation of studying such effects at a fusion power level of 5-10 MW, compared to the 1-2 MW achieved in November 1991 by JET. The results to date and expected in the next few years from TFTR, JET and JT-60, combined with results from a number of smaller tokamaks in the U.S. and elsewhere, are providing the data and scaling law verifications required for establishing the major parameters of ITER. The results from these experiments provide the scientific underpinning and technical credibility for the reference scenario development pathway.

The Tokamak Physics Experiment (TPX) has as its mission "to develop the scientific basis for a compact and continuously operating tokamak fusion reactor." This mission statement was developed by the TPX Project and endorsed by the TPX National Council (4). According to that report, the "TPX will play the important program role of determining whether the tokamak approach can evolve smaller, less expensive, and more attractive fusion reactors than are forecast using conventional physics rules." By "conventional physics rules" the report means those rules which are being used to design ITER.

ITER, the International Thermonuclear Experimental Reactor, has as its "overall programmatic objective" to "demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes" (5). According to the international agreement signed by the U.S., European Community, Japan, and Russia, "ITER would accomplish this objective by demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion energy for practical purposes."

The Materials Test Facility is a high-flux, high-availability, small-volume 14-MeV neutron facility dedicated to irradiation testing to high fluences of candidate fusion reactor materials. It has been a long-recognized need in fusion development plans, but has always been deferred while funding was sought to construct plasma confinement devices. Although it is shown in Figure 1 as beginning construction at about the same time as ITER, the process for securing international commitment to construct this facility is less certain than for ITER. Nevertheless, an active process to secure international commitment to begin joint design is underway.

The Blanket Test Facility is a larger-volume 14-MeV neutron facility with the purpose of irradiation testing of large components. Design concepts for this facility are based on plasma devices, such as driven tokamaks or magnetic mirrors. The tests which could be undertaken in this facility might largely duplicate those which could be undertaken during a second phase of ITER operation (labeled "Nuclear Technology" on the ITER line of Figure 1), but the tests in a Blanket Test Facility might occur 5-10 years earlier than in ITER and thus be available as design input for the Demonstration Power Plant (as shown by the downward arrows on Figure 1), as opposed to ITER test data that might only be available during DEMO construction. These projections assume of course that the DEMO is constructed on the time scale indicated.

The statement of mission, goals and objectives of the Demonstration Power Plant (DEMO) are currently under planned review as part of a DOE-funded study called the STARLITE Project (6). The DEMO is expected to be a plant that demonstrates all the technical features that might be used in a commercial plant and establishes the licensing and operating procedures for proceeding with commercialization.

The Core Program element is a "catch-all" category for the many ongoing physics and technology issues which are the subject of theoretical and experimental investigation at many sites, the results from which provide the scientific underpinning and technical confidence to proceed with the major construction projects.

VARIATIONS ON THE REFERENCE SCENARIO

One way to proceed with development pathways analysis is to consider variations on the reference scenario. In this way, one has the benefit that impact on the reference scenario, including development cost and schedule, as well as technical implications, are more readily identified and discussed.

Questions that might be asked include: (1) Are there other large development facilities that may be either required or desirable? (2) Alternatively, could the fusion program reach the goal of commercial power with fewer large development facilities? (3) Is there a different mix of large facilities that could accomplish the goal at lower cost or on a faster schedule? (4) How might the pathway change if the desired DEMO was not based on the tokamak concept? (5) How might the pathway change if the desired DEMO was not based on the deuterium-tritium fuel cycle? (6) How might the pathway change if the commercial application was other than electric power?

In this report, the discussion will be limited to questions 1 through 3.

WEAKNESSES OF THE REFERENCE SCENARIO

A number of weaknesses of the reference scenario (Figure 1) can be and have been identified in various program discussions and documents. These include the following.

(1) It depends on an unprecedented degree of international collaboration.

(2) It depends on Congressional authorization of overlapping multiple facilities, both national and joint international projects.

(3) The next key facility planned for authorization, ITER, will cost multibillions of dollars and, consequently, its schedule could either slip, or possibly the project might not be able to secure the required funding for the requisite number of years (including a lengthy and costly operations phase).

(4) Even with international sharing of the costs of building the three facilities shown as "international programs," the national budgets will require significant growth that will be very difficult to obtain.

(5) Although the Blanket Test Facility has a constituency, it is not a recognized need among all of the international parties.

(6) ITER is unlikely to incorporate a number of advanced features that are deemed essential for the DEMO.

(7) Unlike fission reactor development wherein many nuclear reactors had been built and operated prior to the construction of a nuclear power plant, the fusion reference scenario envisages only a very few fusion devices prior to DEMO.

(8) The first production of electricity from fusion does not occur until well into the future (post 2025).

FIRST VARIATION

As a first variation on the reference scenario, consider the effect of delaying the ITER schedule and combining the missions of DEMO and ITER. This scenario is shown in Figure 2. The motivation for looking at this variation is to address weaknesses 2, 4, and 6 above, namely, this variation reduces the degree of overlapping of facilities, ameliorates near-term budget impact and allows ITER to incorporate more features deemed essential for DEMO. Indeed, ITER becomes the DEMO. ITER/DEMO, in this scenario, begins construction about 7 years later than the original ITER, but about 10 years earlier than the original DEMO. The date of first production of electricity is unchanged from the reference scenario.

The near term program costs are reduced by the slippage of ITER, and the overall development costs are reduced by the combining of ITER and DEMO in one facility. The technical risk is obviously increased.

This variation also addresses weakness 3, by recognizing that the schedule for ITER may slip in any event and consequently this variation actually may be a natural evolution of the reference scenario.

For this variation to be a realistic backup scenario to the reference scenario, it would be necessary that more serious attention be given to the design and construction of the Blanket Test Facility than is currently the case. Also, the technical issues associated with combining the ITER and DEMO missions would have to be carefully analyzed.

This variation has the weakness of postponing obtaining physics data on ignition and burn. This weakness could be alleviated by adding an Ignition Physics Experiment to the scenario. This would result in a new variation on the pathway and obviously would entail additional costs.

PILOT PLANT VARIATIONS

In many technologies "pilot plants" have been constructed in advance of full scale facilities. Such plants have had the characteristics of small size, low capital cost, and a limited set of objectives, while still having the integrated performance deemed necessary to gain experience with the operating characteristics of the new technology. In combination with other development activities, they have provided essential confidence and experience leading to successful commercialization.

In a recent study (7,8) a Pilot Plant was proposed whose mission would be "to demonstrate energy production from fusion in a power plant configuration at the lowest practicable cost and the earliest possible time." Electric utility personnel would be involved directly in the planning, design and operation of the plant. This would permit them to gain early experience in the licensing, operations, and maintenance issues associated with fusion. Including a pilot plant in the development pathway to fusion addresses weaknesses 7 and 8 of the reference scenario, namely it increases the operational experience base with fusion facilities and demonstrates the capability to generate electricity at an earlier date than DEMO. It also plays the important role of involving the electric utilities directly in fusion development at an earlier date.

One possible variation is to simply add the pilot plant to the reference scenario as an additional facility. This addresses weaknesses 7 and 8 of the reference scenario, but puts additional stress on the budget requirements for development. This variation is analyzed in reference 7. It is shown in Figure 3.

Another possible variation is to combine the missions of the Blanket Test Facility (BTF) and the Pilot Plant. Indeed, it was during, and largely as a result of, the Pilot Plant Study, that renewed community interest in a driven-tokamak version of the Blanket Test Facility (also called a "Volumetric Neutron Source") developed. This possibility is due to the many similarities among the technical designs for a tokamak BTF and a small Pilot Plant. This variation is shown in Figure 4. This variation is actually the reference scenario with an added mission for the BTF. Consequently its cost should be similar to that of the reference scenario.

A COMBINED VARIATION

Another variation (Figure 5) results from combining features from both Figures 2 and 4, i.e., combining the missions of BTF and PILOT in the near term, while slipping the ITER schedule and combining its mission with the DEMO in the long term. This variation results in the lowest cost development path considered in this report. It has the advantage relative to that of Figure 2 that electricity-generation issues are addressed earlier, while maintaining the cost savings features implicit in Figure 2.

DEVELOPMENT COST IMPLICATIONS

The above discussion treats only a few possible cases of interest. Ongoing development pathways analysis must also address variations in the cost, technical risk and technical credibility of various scenarios. No such quantitative analysis has yet been done on these issues. However, an approach to analyzing the cost/schedule relationships to technical pathways was developed and applied previously (9) and can readily be applied to the pathways analysis process.

REFERENCES

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4. Review Committee Report on the Conceptual Design of the Tokamak Physics Experiment, DOE/ER-0592, April 1993.

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7. Stephen O. Dean, et al., "An Accelerated Fusion Power Development Plan," J. Fusion Energy, Vol. 10, No. 2, p. 197, 1991.

8. Stephen O. Dean, et al., "Pilot Plant: An Affordable Step Toward Fusion Power," J. Fusion Energy, Vol. 11, No. 2, p. 85, 1992.

9. Fusion Power by Magnetic Confinement Program Plan, ERDA-76/110, 5 vols., July 1976.

Figure 1. *U.S. MAGNETIC FUSION STRATEGY*

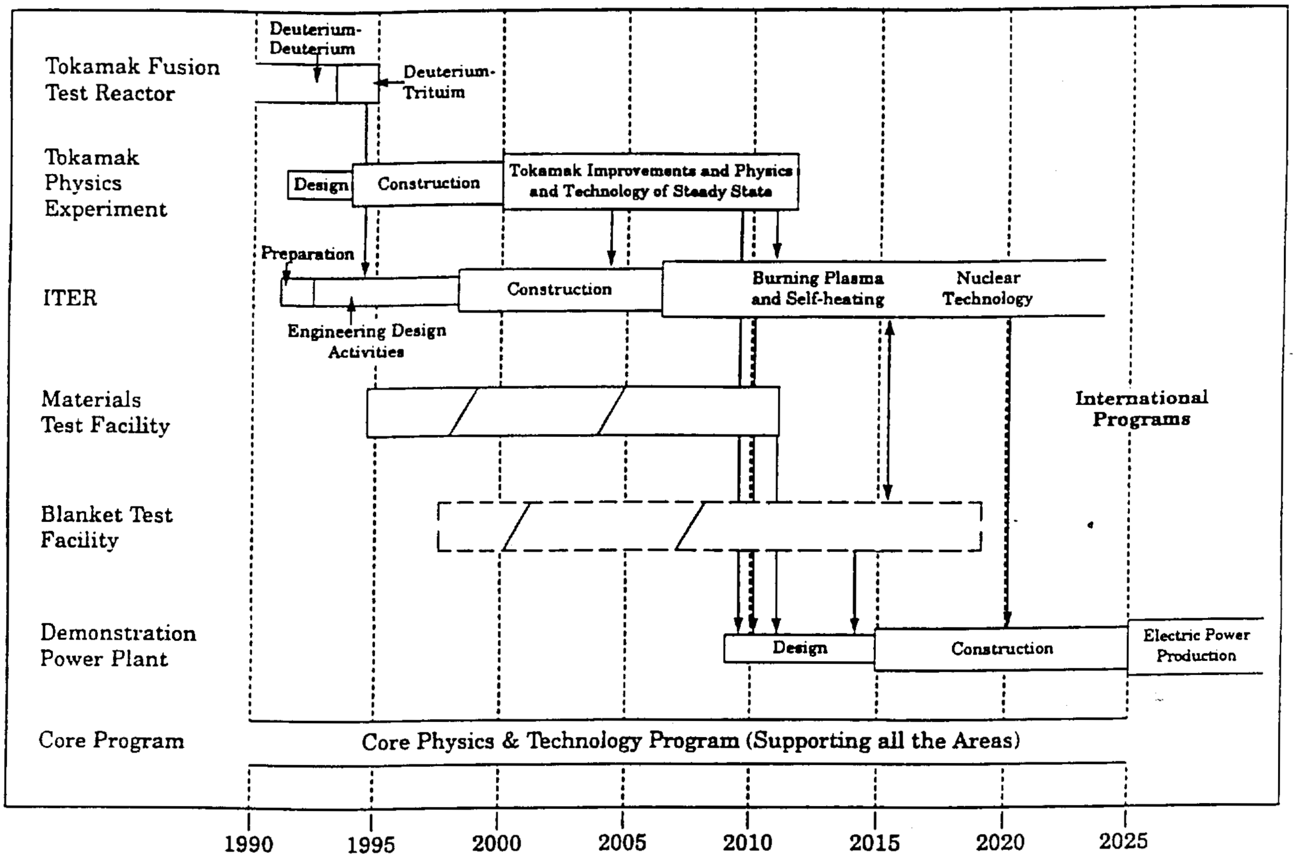

Figure 2. **Variation 1: Combined ITER/DEMO Missions**

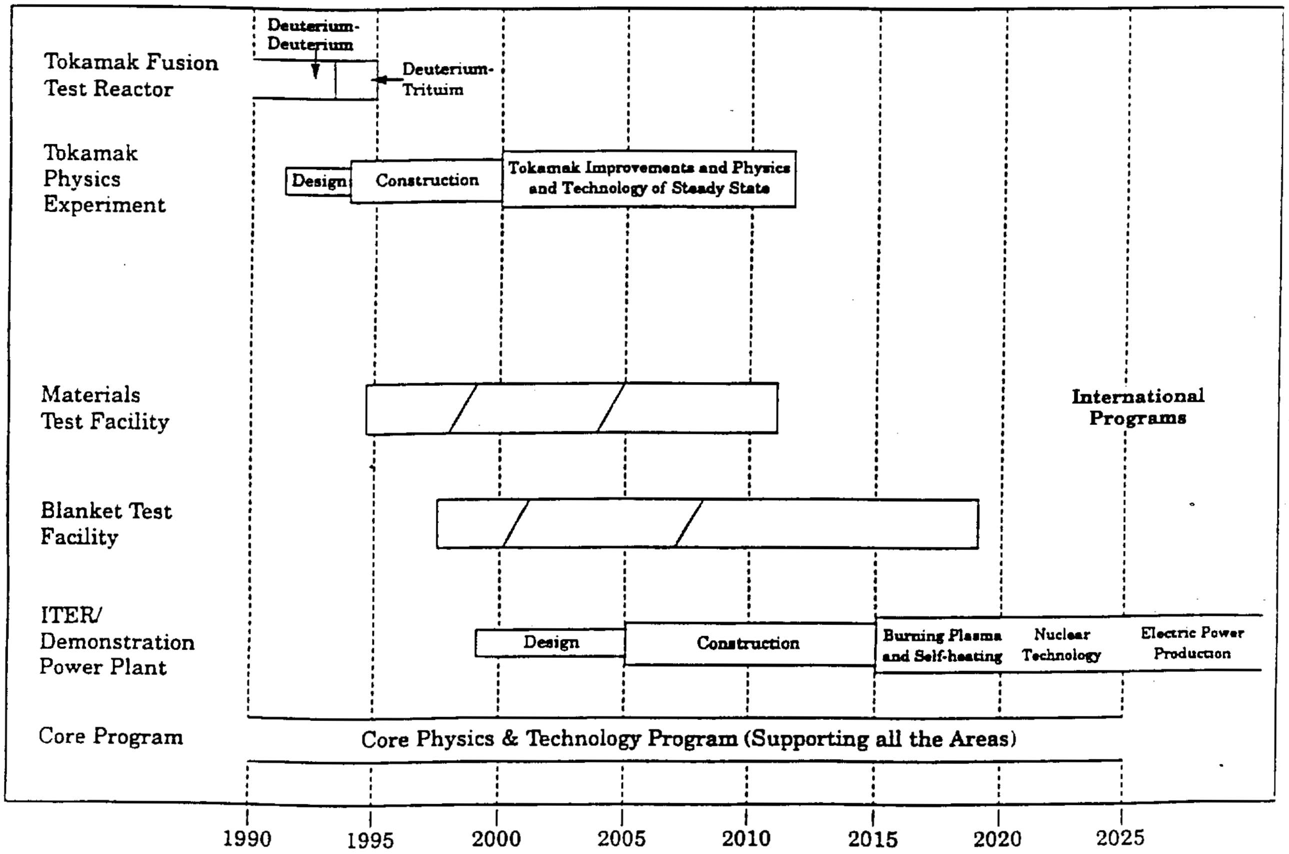

Figure 3. Pilot Plant Variation (a): Addition of Pilot Plant

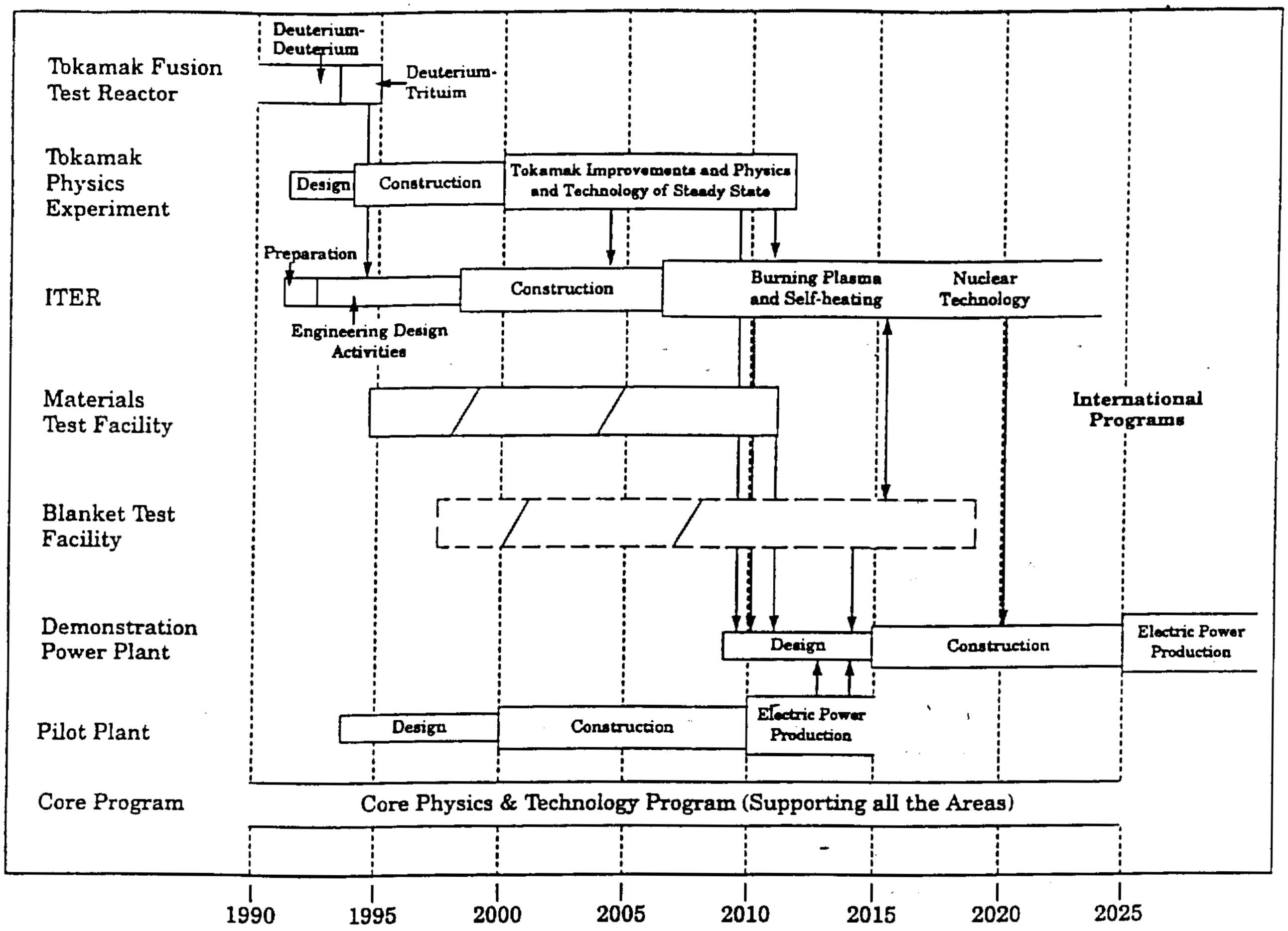

Figure 4. Pilot Plant Variation (b): Combined BTF/Pilot Plant Missions

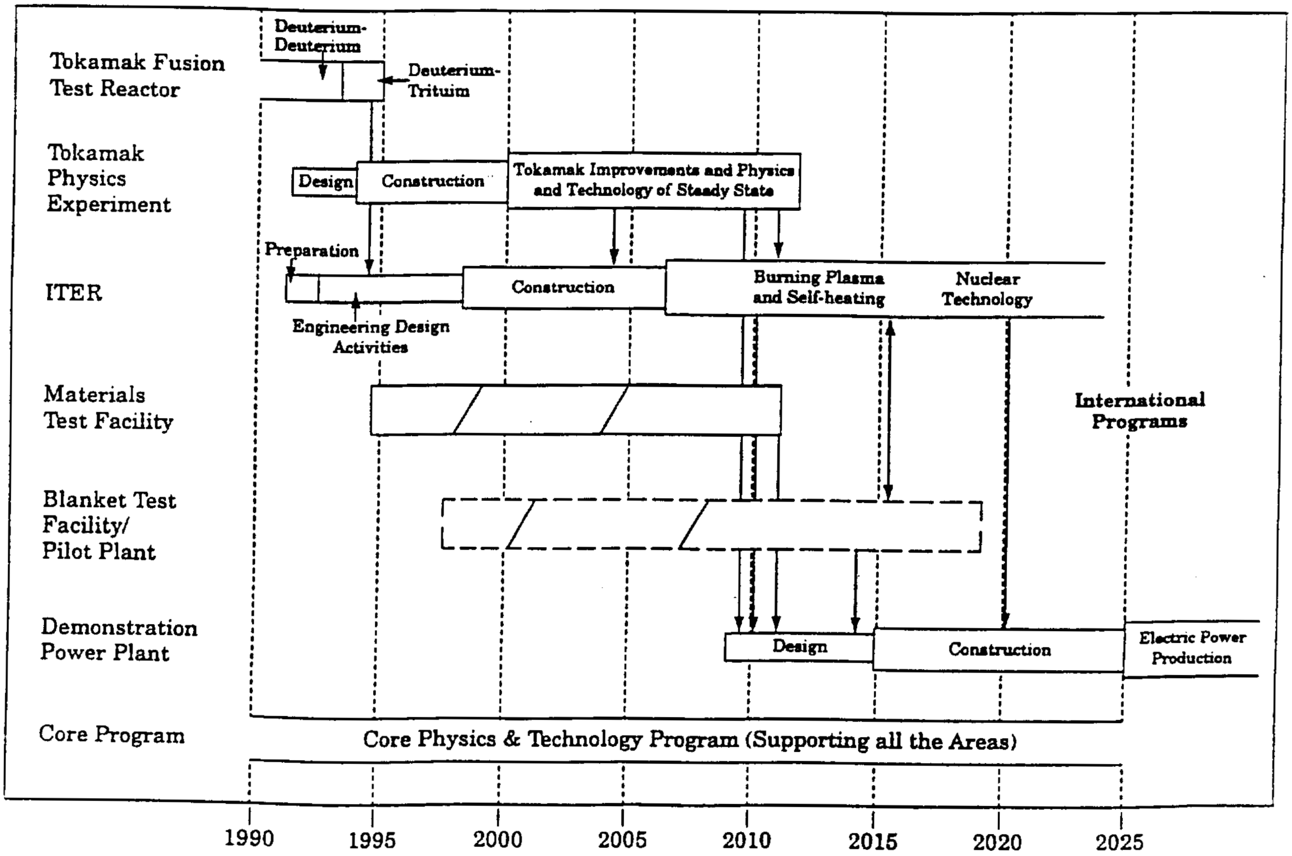

Figure 5. Combined BTF/Pilot Plant and Combined ITER/DEMO Missions