2002 Fusion Summer Study
Subgroup E4 - Development Pathway Subgroup

Draft by: Farrokh Najmabadi, Kurt Schoenberg, Rob Goldston, Dale Meade, Hutch Nielson, Craig Petty, Martin Peng, Paul Rutherford, John Schmidt, John Sarff

With input from: Joe Minervini, Nicolai Martovetsky, Mike Ulrickon, Rich Mattis, Dave Rasmussen; Brad Nelson, Dave Petti, Scott Willms, Steve Zinkle, Mark Tillack

1. Introduction

A burning plasma experiment is a key step in developing fusion. The realization of fusion, however, requires scientific progress in many other plasma physics and technology areas. Examples include: steady-state advanced plasma modes with low recirculating power and high β, steady-state operation of impurity control/particle exhaust system under prototypical particle and energy fluxes, development of low-activation material and fusion power technologies, *etc.* An important discriminator among various embodiments of burning plasma experiments is the flexibly to examine these scientific challenges, other than burning plasma physics, toward development of fusion.

The aim of this subgroup activity is to identify the technical requirements and metrics for the development of fusion as an energy source and to evaluate and assess fusion development path based on the different proposed burning plasma experiments. In addition, the subgroup has considered how alternative concepts contribute to and are folded into a fusion development path. In this respect, the scope of subgroup activity is limited to MFE concepts that are at least at the proof of principle development stage (compact stellarator, RFP, ST, and tokamak).

Commercialization of fusion power is the goal of fusion development. Accordingly, the fusion development pathway encompasses all scientific and technology development required for such a power plant. Top-level metrics and goals for commercial fusion power have been identified in various national fusion programs. These metrics and goals are described in section 2.

Many aspects of plasma physics and technology needs of a fusion power plant have not yet been fully demonstrated on experiments. Conceptual design and analysis of fusion power plants haven been carried out since the early days of fusion research to understand the characteristics of potential fusion energy systems. Through detailed and integrated design and assessment of fusion concepts as power plants, these studies synthesize a wide variety of fusion R&D results, and provide feedback to the fusion community on the scientific directions that carry greatest leverage for fusion energy. Because power plant studies necessarily need to be forward looking in both physics and engineering design, subjective choices will always need to be made in extrapolating present understanding and experience. These choices vary due to different program needs. Because of the different degree of extrapolation utilized in power plant studies, intercomparison of these design studies provide a wealth information on the potential of fusion as an attractive and sustainable energy source and directions for fusion development. For this purpose, we have considered the applicable ARIES design, *e.g.*, ARIES-RS, ARIES-AT, *etc.*, or similar studies overseas, *e.g.*, Japanese SSTR and A-SSTR as well as on-going European Power Plant Conceptual Studies.

Section 3 presents fusion technology requirements and R&D needs. Contributions of various burning plasma experiments to fusion technology development are also discussed.

Section 4 uses the results from various power plant studies to identify physics regimes of operations for an attractive fusion power plant that satisfy metrics and goals of section 2.

Section 5 discusses how alternative concepts contribute to and are folded into the fusion development path. In particular, contributions of a tokamak burning plasma experiment to development path of other concepts are explored.

This information are then used in section 6 to scope out the impact of the proposed burning plasmas experiments on development path for fusion energy: We have considered the following cases, 1) Proceeding with IGNITOR-class experiment, 2) Proceeding with FIRE-Class experiment, 3) Proceeding with ITER-class experiment, and 4) Not proceeding with any burning plasma experiments.

2. Requirements for Fusion Power

2.1. Top-Level Metrics and Goals

The “official” US economic and environmental metrics for commercial fusion power plants are given in Table 2.1 (from FESAC Panel of priorities and Balances [1]). These metrics provide a set of standard to judge the success of fusion development. Similar metrics and goals have been “officially” identified in Japan (from *The subcommittee of the fusion council for fusion development strategy*, “Report on the technical feasibility of fusion energy and extension of the fusion program and basic supporting researches” [2]). Operational and environmental metrics have also been developed in EU as part of the European Power Plant Conceptual Study [3] (no cost goals are given). These top-level metrics and goals provide clear guidelines in arriving at a fusion development scenario.

Safety & environmental goals in various world programs are similar. These goals require that fusion core is constructed entirely of low-activation material. Fusion development path, therefore, should include 14-MeV neutron source for accelerated fluence testing of low-activation material. In addition, extensive R&D is required to develop fusion power technologies (such as blankets and power-producing plasma-facing components) that utilize these materials.

Operational goals of high capacity factor require early integration of physics and technology in order to develop extensive reliability/maintainability data.

European programs state that fusion power costs should be competitive to other sources of energy but no quantitative values are given citing unknown external factor (such as Carbon Tax) that may impact the cost of competitive energy sources. Japanese goals for cost of electricity are quoted in Ref. 2 as 7 yen/kWh ("desirable for utility"), <10 yen/kWh ("initial fusion power plant"), and an upper bound of 15 yen/kWh. These cost targets correspond to 0.7 to 1.5 times of present cost of electricity (See Fig. 2.1). These goals are very similar to US goals (Fig. 2.2 and Table 2.1). Both Japanese and US cost goals require development of high performance plasmas as well as high performance fusion power technologies (*e.g.*, blankets) and have a strong influence on fusion development scenarios.

Table 2.1
Anticipated Economic & Environmental Metrics for Commercial Fusion Power Plants
(from report of FESAC Panel on Priorities and Balances [1])

Metric	**Goal**
Cost of Electricity	5-6 c/kWh ($1998)[a]
Dose limit to insure that no public evacuation plan is required	<1 rem at site boundary
Occupational dose to plant personnel	<5 rem/y [b]
Rad-waste disposal criterion	Class C & minimization of waste hazard and volume [c]
Fuel cycle closed on site	Yes
Atmospheric pollutants (CO_2, SO_2, NO_x)	Negligible [d]
Capacity factor	> 80%
Major unscheduled shutdowns	<0.1 per year
Must Provide for operation at partial load condition	50% of full power

[a] Includes environmental and safety credits.

[b] Application of ALARA principles expected to result in significant lower doses.

[c] Thus permitting (i) recycling of plant material, (ii) on-site shallow land burial of waste components at end-of-life.

[d] Relative to competing technologies

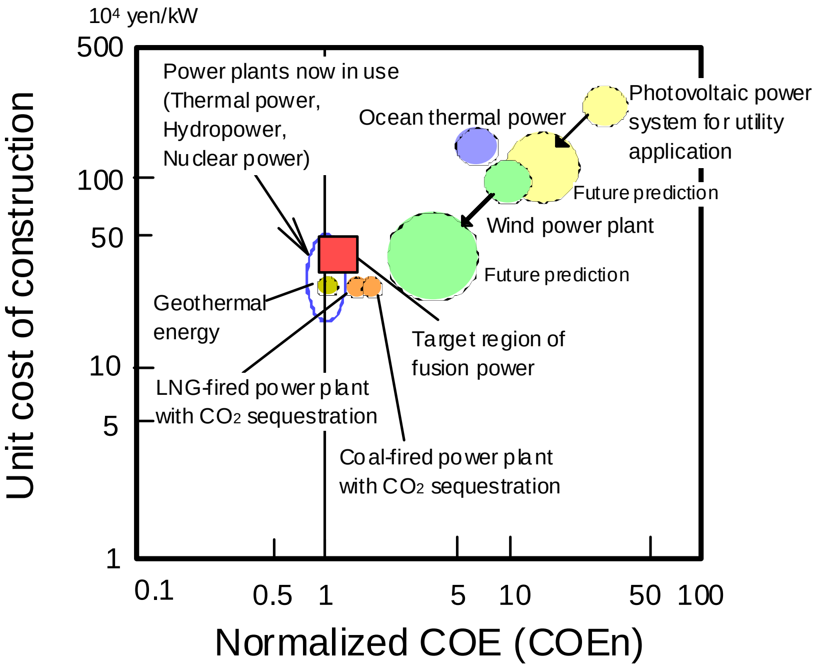

Fig. 2.1. Japanese target region of fusion power plant (COEn=0.7-1.5, construction cost=30-50x10^4 yen/ kWe) and the location of other power plants in the COE (cost of electricity) – construction cost diagram. (from Ref. [2]).

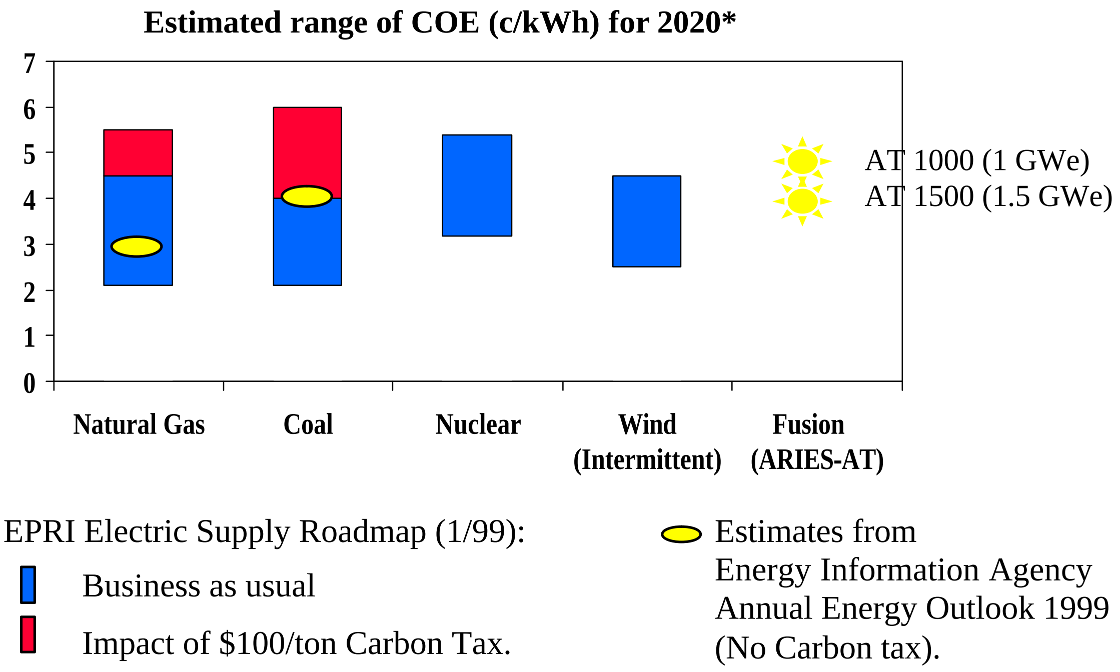

Fig. 2.2. Estimated cost of electriy from various sources of energy in 2020 (date from Fusion Summer Study 1998).

3. Fusion Technologies

The realization of practical fusion power will require substantial technology development. Many of the required technologies are specific to the nuclear aspects of a fusion power plant (*e.g.*, low-activation materials, tritium technologies, *etc.*), while others are strongly affected by the intense neutron and heat fluxes from a fusion plasma (*e.g.*, plasma-facing components, rf antennas, *etc.*).

Fusion technology development will encompass activities of three different types:

1. <u>Base program in fusion technology</u>. The base program in fusion technology, including many smaller-scale test facilities, provides the foundation for all advances in technology development and application [4]; the program will expand substantially with increased focus on power plant development.

2. <u>Large-scale independent test stands</u>. Certain technologies require special facilities and test stands independent of the plasma confinement experiments. The development of low-activation materials will be carried out almost exclusively on facilities of this type, which will be constructed and operated essentially in parallel with the next generation of burning plasma experiments. For many other technologies also, large-scale independent test stands are needed to develop the technology in a generic way, sometimes for use first on burning plasma experiments before further development to meet power plant requirements; technologies of this sort include negative-ion neutral beams, rf systems, tritium systems, *etc.* In still other cases, large-scale test stands will be needed to validate specific designs of technology components for a particular power plant-like plasma facility; such test stands have already been built to test components for ITER, including toroidal-field and poloidal-field coils, remote handling systems, etc.

3. <u>Testing in burning plasma experiments</u>. Present-day tokamaks and other plasma confinement experiments have already been able to test key advances in some technologies, especially those relating to plasma heating and current drive and plasma power handling. Burning plasma experiments will extend enormously the range of relevant conditions accessible in tokamaks, because of the higher power density and the presence of a substantial neutron flux. Burning plasma experiments will also be major drivers for advancing technologies relating to remote handling and maintenance and for validating approaches to fusion power plant safety.

For present purposes, it is not necessary to describe the base program in fusion technology, but it is important to assess the relative roles of large-scale independent test stands and burning plasma experiments in developing fusion technology to meet the power plant goal.

It is important to distinguish between plasma support technologies (such as magnet, heating) and fusion power technologies (such as low-activation materials, blanket, power-producing plasma facing components, *etc.*). Plasma support technologies have been continuously developed in parallel with confinement experiments. In most cases, plasma support technologies required for a burning plasma experiments are similar to those of a power plant. As such, burning plasma experiments provide a test bed for integration and advancement in these technologies.

Fusion power technologies are at much lower level of maturity. Contribution of a burning plasma experiment to advancement of these technologies depends on the capability of fielding test modules on a BPX as well as power and neutron flux and fluence available. Development of fusion power technologies requires additional facilities are described in Section 6.

3.2. Methodology

The Development Path Subgroup views the goal of fusion development to be the realization of a commercial fusion power plant. Accordingly, the fusion development pathway encompasses all technology development required for such a power plant. For this purpose, a fusion power plant may be exemplified by the applicable ARIES design, *e.g.*, ARIES-RS, ARIES-AT, *etc.*, or similar studies overseas, *e.g.*, SSTR. There will be one or more intermediate steps between the burning plasma experiment and the power plant, variously called ETR, DEMO, etc., but the exact characteristics of the intermediate step(s) will depend on the burning plasma experiment that is implemented and on the magnetic confinement concept selected for power plant development. For present purposes, the "end-product" of fusion technology development should be a commercial power plant.

The Development Path Subgroup obtained input from the Technology Task Leaders (T1–T5, excluding T6, cost) in response to the following three requests:

1. List the primary issues for each task area requiring technology development;

2. Identify the facility needs to address these issues in terms of the applicable technical requirements (*e.g.,* heat flux, neutron flux/fluence, pulse length, duty-cycle, *etc.*), including any thoughts on possible facilities costs;

3. State what contributions the three candidate burning plasma experiments (IGNITOR-class, FIRE-class, and ITER-class experiments) would make to address these issues.

The information generated by this process is discussed below and is described below and summarized in the Tables 3.1-3.7. This information is augmented by the subgroup itself in the area of fusion power technologies, *i.e.,* blankets (Table 3-8).

3.3. Generic requirements

In addition to meeting specific performance objectives, there are three generic requirements that must guide fusion technology development in order to qualify systems and components for power plant application:

1. <u>Reliability/Availability</u>. For many components, e.g., magnets, negative-ion neutral beams, rf systems, pellet injectors, *etc.*, reliability will be a key goal of the development program on independent test stands, and specific reliability metrics must be met before such components are installed on a burning plasma experiment or other fusion facility. For other components, *e.g.,* plasma-facing components, ICRF antennas, tritium systems, *etc.*, the burning plasma experiment itself will provide a major step toward meeting power plant reliability goals. In

this context, the large differences in duty-cycle/availability goals of ITER versus the two copper-magnet burning plasma experiments should be highlighted. ITER has a duty-factor of about 0.25, *i.e.*, one 7-minute full-power burn pulse every 30 minutes, whereas FIRE has a duty-factor of only 0.002, *i.e.*, one 20-second full-power pulse every 3 hours; the duty-factor in IGNITOR is even smaller, namely about 0.0003, *i.e.*, a 4-second full-power pulse with a 4-hour cool-down between pulses. The duty-factor of ITER is higher in current-driven operation, where pulse lengths in excess of 1,000 seconds are possible. Also, ITER is designed for up to 30,000 full-power pulses (10,000 in the first DT plasma phase), versus FIRE for 3,000 pulses. These differences imply that ITER would be the strongest driver for developing the reliability/availability of technical systems and components.

2. <u>Maintainability</u>. Maintainability will be a key requirement in the design of essentially all power plant components and must be an important consideration in the technology development program. Remote handling of all in-vessel and many ex-vessel components is a feature of both ITER and FIRE, but the larger size/weight of individual components and the overall configuration may make the ITER program more prototypical of a power plant. The remote maintenance capabilities of IGNITOR are limited to in-vessel components.

3. <u>Compatibility/Integration</u>. Many of the components of a fusion power plant interact importantly with other components. For example, all in-vessel components are strongly interactive, so materials and coolants for ICRF antennas must be compatible with those chosen for the high-heat-flux plasma-facing components. Tritium and helium pumping system requirements are strongly affected by the choice of plasma-facing material, because of the co-deposition issue, and they, in turn, affect the external tritium separation system. Superconducting magnets, although developed mainly on independent test stands, will be subject to nuclear heating in a power plant, and their insulators will be vulnerable to radiation damage. Accordingly, all fusion technology components should be designed taking the relevant compatibility constraints and interactive relationships into consideration and, to the maximum extent permitted by cost and other considerations, their development and testing should be done in “integrated” facilities so as to allow these interactions to occur.

3.4. Technology-specific requirements and contribution of BPXs

From Tables 3.1-3.8, it can be seen that the contributions of the three candidate burning plasma experiments may be summarized as follows.

Magnets

Recent ARIES tokamak power plant designs (*i.e.*, ARIES-AT) as well A-SSTR2 use high-temperature superconducting (HTS) magnets. The basic development of HTS magnets will be done by industry, driven by many promising applications other than fusion. The specific application of HTS magnets to fusion lies in the future, but it is likely to proceed in a generally similar fashion to the application of Nb_3Sn magnets, since most of the key technical issues are similar. Specifically, development of strand and conductor will be followed by manufacturing R&D aimed at producing high-quality cable in the quantities needed for fusion applications. The designs and manufacturing techniques for the coils of a specific fusion power plant facility will then be validated by constructing and operating large magnet test stands, as has been done for ITER with the Nb_3Sn poloidal-field and toroidal-field model coil test facilities.

It should be noted that the application of any superconductor to a large fusion project would always lag very far behind advances at the frontier of the technology. This is due to the pace at which such advances occur, the long time needed to design and build large fusion experiments, and the need to avoid technical risk. This characteristic of technology application will be shared by other fusion technologies to a varying extent. This is acceptable in the present phase of fusion, but at some point it will be necessary to focus the magnet development program for fusion applications on a conductor that meets the minimum requirements for the first generation of commercial power plants, leaving further optimization to subsequent generations.

Clearly, neither FIRE nor IGNITOR would contribute to superconducting magnet development. The contributions of the Nb_3Sn superconducting magnet program for ITER have been substantial, but most of these have already occurred and are reflected in successful operation of the two model-coil test facilities; more information will come from these facilities in the coming years. In particular, a PF Insert, currently under construction, will be tested in the background field of the Central Solenoid Model Coil (CSMC) facility. All tested inserts were exposed to several thousand load cycles in the CSMC, as will be the PF insert also. The successful operation of ITER itself would represent a major advance in achieving reliability/availability goals for superconducting magnets for fusion. Operation of ITER would also provide valuable information on the integration of superconducting magnets into a power plant-like D-T tokamak, especially in regard to the steady-state removal of nuclear heating and the possible effects of plasma transients such as disruptions. A much earlier test of magnet integration in a fully superconducting tokamak (*i.e.*, with superconducting OH solenoid and PF coils) will come from KSTAR, albeit without any nuclear effects.

Plasma-Facing Components and Heat Removal

The deployment of PFCs in burning plasma experiments will be an essential element in their development for fusion power plant application. However, testing of advanced PFC concepts (*i.e.*, power producing) would be extremely limited in IGNITOR, because of the very short pulse length, absence of a divertor and lack of active first-wall cooling. The ability to test advanced PFCs is considerably improved in FIRE, because of the divertor and a 20-sec flattop, which is sufficient for thermo-mechanical testing of first-wall components. Clearly, however, ITER is the best alternative for testing advanced PFCs and first-wall/blanket systems, because of superior access for test-modules and a 400-sec flattop in inductive operation, which is long enough for thermal equilibrium in the blanket. Although ITER, alone among the three options, has significant neutron fluence, this is insufficient to reach saturation of irradiation effects on material properties.

Testing for reliability/availability is important for PFC development, because of the very large number of tiles bonded to actively cooled heat sinks and subjected to thousands of thermal cycles. Because of the large number of cycles, ITER would be the best device to obtain reliability/availability data, followed by FIRE and then IGNITOR.

The ITER design has CFCs for the high-heat-flux divertor surfaces, with the possibility of replacement by tungsten if tritium retention is too large. The FIRE design has a tungsten divertor plate. Both ITER and FIRE have beryllium tiles covering the first wall; IGNITOR has a molybdenum vessel wall.

Heating and Current Drive

For NBI and ECH, the primary requirements of the development program are full-scale independent test stands. For power plant applications, highly reliable, steady state systems will be required. Access considerations preclude the use of NBI in IGNITOR, and NBI is not part of the baseline design for FIRE. The high magnetic fields in IGNITOR and FIRE also precluded ECH, which would require gyrotrons at frequencies (˜ 300 GHz) well above the range of present development programs. ITER will employ negative-ion NBI at 1-MeV and ECH at 170 GHz, and development programs are underway (now mainly outside the U.S.) to provide steady-state systems to meet these requirements.

For ICRF, a combination of development on full-scale, independent test stands and deployment in burning plasma experiments is needed. By providing multi-MW component testing in a high-heat-flux and neutron environment, IGNITOR, FIRE and ITER would all contribute very significantly to the development and qualification of ICRF concepts for power plant application.

To develop LHH for power plant application, a combination of independent test stands and deployment in burning plasma experiments would be needed. Although, none of the three machines has selected LHH as a necessary component of its heating and current drive system, any of them could be used to test the basic heating concept in a power plant-level plasma.

Fueling and Pumping

For pellet fueling, a combination of development on tritium-compatible test stands and application of tritium pellet injectors to burning plasma experiments is needed. In this latter regard, IGNITOR, FIRE and ITER would all contribute very significantly.

For pumping, tritium-compatible cryogenic test facilities are needed, and additional facilities will be needed to develop concepts of liquid walls for power plant application. Both FIRE and ITER would contribute significantly to the testing of cryogenic pumping concepts for D-T plasma, because of their need to exhaust helium. IGNITOR would not contribute significantly in this area, since it has no divertor and will not actively pump helium.

Vacuum Vessel and Remote Handling

For the vacuum vessel, especially if it is used as the primary safety barrier, the development of a design code acceptable to regulators will be needed at the power plant stage (and may already be needed for ITER), but the particular issues encountered in the designs of the three burning plasma experiments will have to be solved in device-specific R&D programs. Both FIRE and ITER will incorporate key features of a power plant-like vessel, including remote cutting and welding of vessel joints, and FIRE will also require active plasma stabilization coils; in these respects, the contributions of IGNITOR will be much more limited.

For remote handling, a broad development program is required, including both generic facilities and device-specific facilities to test maintenance operations prior to their deployment on an actual device. Such a program is underway (outside the U.S.) for ITER, and R&D programs for FIRE and IGNIATOR have been formulated. The in-vessel and ex-vessel maintenance tasks to be carried out remotely in FIRE and ITER are generally similar, although the components are usually larger and more complex in ITER.

Safety and Tritium

Successful operation of any of the burning plasma experiments without significant safety-related incidents would have a positive effect on public acceptability of fusion.

However, IGNITOR and FIRE have only modest inventories of tritium and small-to-moderate-size energy sources. Their regulatory approval will provide little demonstration of the safety and environmental potential of fusion power plants. By contrast, ITER is projected to have power-plant-relevant hazards - the large inventories of tritium and activated dust, and the large energy sources that could mobilize those inventories - and has implemented safety limits to mitigate those hazards. ITER has developed a high degree of safety integration in the design at the system and subsystem level, and good depth and rigor of the safety analysis. The detailed safety R&D that has been performed has answered the key safety questions important in the safety design and safety analysis. ITER poses many, if not most, of the safety concerns associated with a fusion power plant. Thus, the regulatory approval of the safety approach used by ITER, concurrence and validation of the safety analysis, and safe operation of the facility would in large part demonstrate the safety and environmental potential of fusion power plants.

The safety-related issue of tritium retention in PFC materials must be addressed and resolved even in a FIRE-class facility. Although the tritium inventory at FIRE would be in the same general range as at TFTR, the maximum tritium burned per pulse would be about 300 times higher, and the tritium burned over the machine's lifetime would be about 6,000 times higher.

In regard to tritium technology, both IGNITOR and FIRE would provide some useful operating experience, but neither would advance the state-of-the-art, since their needs could be met with present-day tritium systems.

On the other hand, ITER would represent a major step forward in tritium technology. The essential feature of ITER is that, because of the very large tritium throughput, the tritium system operates quasi-continuously in a closed cycle. The tritium flow rate in ITER is substantially higher than has previously been achieved in test facilities, and the tritium recycle time through the isotope separation system is substantially shorter. For these reasons, the tritium R&D program for ITER and experience with the tritium systems during ITER operations would be of very great value in preparing for a subsequent device.

Materials

The development of radiation resistant (low activation) materials for fusion power plants requires, primarily, an intense neutron irradiation source. In the near term, fission power plants will continue to be used as irradiation facilities. However, to provide the spectral response, higher flux and higher fluence needed to develop, test and qualify materials for a fusion power plant, a dedicated Fusion Materials Irradiation Facility (such as the proposed international facility, IFMIF) is required. IFMIF is designed to irradiate a broad range of structural and blanket materials, and is considered the key facility for the development and qualification of fusion structural material. The IFMIF is an accelerator-based neutron source and, within its high flux volume (>2 MW/m^2 neutron flux in ~ 500 cm^3 of volume and > 5.5 MW/m^2 in ~ 100 cm^3 of volume) as presently designed, the displacements per atom per full-power-year can be up to 2 times higher than in a fusion power plant and about 60 times of ITER. Utilization of the > 5.5 MW/m^2 region of IFMIF allows accelerated testing, since the anticipated lifetime dose of 150-200 dpa can be achieved for a full range of mechanical and physical properties, specimen geometries if two materials at 3 to 4 temperatures. Power plant-relevant irradiation parameters, such as the hydrogen/dpa and helium/dpa ratios, are closely matched with fusion power plant values.

Of the three burning plasma experiments, ITER has by far the highest neutron fluence (0.3 MW.yr/m^2, 3 dpa average, somewhat larger in high-flux regions), but even this is far below what is needed to qualify materials for a fusion power plant: an irradiation facility is needed to reach power plant-like fluence values.

Nonetheless, a burning plasma experiment offers materials science opportunities in several “niche” areas, mainly non-structural materials, where effects arise at about 1 dpa or less, or where neutron flux is more important than fluence. These include radiation effects on ceramic insulators, optical materials, polymers, diagnostic components and the copper alloys used as heat sinks in all three burning plasma experiments. For these studies, the main requirement is adequate access for test modules and dedicated materials testing ports.

Blankets

Traditional blankets are categorized into solid and liquid breeder variants. During the 1980’s, a relatively broad range of experiments was carried out on tritium breeding and materials activation, tritium extraction and recovery, materials compatibility and thermal hydraulics. Healthy international collaborations supported these activities in both the solid and liquid breeder areas.

During the 1990's, the ARIES integrated design studies team developed conceptual designs for several advanced liquid-breeder blankets. These designs included both self-cooled and "dual-cooled" variants using advanced Rankine or Brayton power conversion cycles. Design innovations sought to increase thermal conversion efficiency and improve availability through emphasis on design simplicity and rapid maintenance procedures. However, at the same time, blanket R&D programs were dramatically reduced and redirected.

Recent R&D in the US has focused on designs without solid first walls, especially "liquid wall designs". The US blanket program now emphasizes fundamental studies of "innovative" design concepts, with experimental activities concentrated mainly on thermal hydraulics. Overall, the scope of research on blanket-specific issues has contracted greatly.

One of the areas that has received inadequate attention historically is system integration and reliability of components. The use of a large burning plasma test facility such as ITER has been viewed by many as an important step in this direction. However, the limited testing volume, testing time and neutron fluence likely will lead to the need for additional facilities. For example, a dedicated burning plasma test facility (a "component test facility" or a "volume neutron source") has been proposed as a supplement to a low-fluence burning plasma experiment such as ITER. A high-fluence, high-volume source of neutrons is likely to be a major element in the fusion development path. Therefore, in any discussion of fusion development pathways, increased attention is needed to articulate a balanced and optimized strategy of both physics and technology advancement.

Table 3.1. MAGNETS

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
Superconducting Magnets: Generic Issues 1. Increase s/c current density - at high magnetic field - with low magnetic hysteresis and coupling loss - understanding of degradation mechanism; reduction or elimination of degradation in Nb_3Sn CICC 2. High-strength alloys for conduits - cryogenic operation - to withstand reaction heat treatment 3. Conductor joints - low-loss, high-stability 4. Radiation-resistant insulators - to allow higher nuclear heating 5. Operation at pulsed fields up to 2 T/s - also effects of transients, disruptions 6. Quench detection/propagation 7. Structural alloys for cryogenic operation - magnet case, intercoil structure	For Nb_3Sn (1 – 7) ITER magnet R&D program - strand/cable long-lengths manufacture - cable-in-conduit conductor production - winding, coil fabrication - CS Model Coil tests at 13 T, = 2T/s - PF Insert tests at 7 T, = 2T/s - Operation of CSMC for ~ 10^4 cycles - TF Model Coil tests at full current - CSMC tests of inserts with other conductors and conduit materials Operation of S/C Tokamaks & Stellarators - LHD and W-7X (NbTi) - LDX (ring) (Nb_3Sn) - KSTAR (Nb_3Sn) - ITER-class (Nb_3Sn) Laboratory-scale test facilities - aim to increase critical current density - develop S/c laced copper conductors	IGNITOR and FIRE No contributions to s/c magnet development For Nb_3Sn ITER R&D Program (including the PF and TF Model Coils) Major: Issues 1, 2, 3, 4, 5, 6 ITER Operation Major: Issues 4, 5, 6, 7 Major: Reliability aspects of Issues 1-3
High-Temperature Superconductors (HTS): Specific Issues 8. Introduce HTSs into fusion - high magnetic field (20 - 25 T) - much lower refrigeration costs 9. Materials manufacture issues - long lengths, reduce cost	For HTSs (8, 9) Laboratory-scale test facilities - ac losses in HTSs under pulsed fields Manufacturing facilities - driven by other applications, e.g. HEP - aim to lower conductor cost	For HTSs No specific contributions to HTSs, but many aspects of Issues 1-7 are generic to all superconducting applications to fusion.

Table 3.2. Plasma-facing components and heat removal

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
1. High-heat-flux power removal - divertor-plate/limiter - 10-100 MW/m2 - radiative mantle - impurity seeding 2. Impact of PFCs on plasma performance - plasma edge temperature 3. Component lifetime and reliability - erosion during normal operation - erosion in disruptions/ELMs - mechanical integrity - neutron radiation damage - reliability/availability over many thousand thermal cycles 4. Integration with in-vessel components - coolant/materials compatibility 5. Power conversion - coolant ? T, flow rate 6. Safety - tritium inventory/co-deposition - effect of coolant leaks	High-heat-flux test-stands (1) - electron-beam facilities - non-magnetic liquid metal facility PMI simulation facilities (2) - particle/materials interaction Erosion simulation facilities (3) - simulation of disruption/ELM loads Neutron damage facilities (1, 3) - PFC-specific materials (W, Be) - irradiation to 10-20 dpa Present tokamaks (2) - PMI phenomena Future tokamaks (1, 2, 3, 4) - integrated PFC performance - pulse 5-10 s for first wall thermal equilibrium - pulse = 100 s for blanket thermal equilibrium Modeling (all) - individual/multiple phenomena - extrapolation to a power plant	IGNITOR Significant: Issue 1 - no divertor - no active first-wall cooling - no access for test modules - design: Mo wall FIRE Major: Issues 1, 2, 4 Significant: Issues 3, 6 - advanced divertor - pulse length sufficient for first wall thermal equilibrium - pulse length too short for blanket thermal equilibrium - limited access for test modules - design: W div, Be-tile wall ITER Major: Issues 1, 2, 3, 4, 6 Significant: Issue 5 - advanced divertor - pulse length sufficient for first wall and blanket thermal equilibrium - superior access for test modules - neutron fluence adequate for some mechanical property tests, but too low (3 dpa) for neutron damage test - design: CFC div (W?), Be-tile wall

Table 3.3. Heating and current drive

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
NBI NB1. Development of long-pulse, MeV-level, reliable negative-ion NB system - reproducible, stable, spatially - uniform negative-ion source - reliable MeV accelerator structure - higher speed voltage switching ICRF IC1. Development of steady-state, multi-MW ICRF antenna - transmission line, tuning system - load and operating-mode tolerance in start-up, ELMs, L/H transitions IC2. Power plant-compatible components - radiation tolerant insulators or all-metal supports ECH/CD EC1. Steady-state gyrotrons at = 150 GHz - multi-MW, tunability advantageous EC2. Low-loss transmission lines - double barrier windows EC3. Launchers/antennas to direct power LHH/CD LH1. Development for power plant application - CW sources at 4-8 GHz, = 1MW - antennas for power/neutron loads - ancillaries for MW CW operation	NBI Full-scale independent test stand (NB1) - 30-MW level ICRF Full-scale independent test stand (IC1) - 50-MW level Access to irradiation test facility (IC2) - neutron and high heat flux ECH/CD Test stand for multi-MW CW gyrotrons (EC1) Transmission line and antenna test stand (EC2, EC3) LHH/CD Full-scale independent test stand (LH1) - individual unit, 1-2 MW Transmission line/antenna test stand (LH1) - could be combined with ICRF/ECH	IGNITOR None: NBI and ECH/CD issues Major: Issue IC1 Significant: Issue IC2 - heating only, no current drive FIRE None: NBI and ECH/CD issues Major: Issue IC1 Significant: Issue IC2 - heating mainly, pulse length allows only limited current drive ITER Major: Issue NB1, IC1, IC2 Major: Issues EC1, EC2, EC3 - pulse length allows fully current-driven plasma operation - ITER contributions include associated MeV NBI and 170 GHz gyrotron development programs - frequency scaling for ECH addressed off-line Note: Although not presently selected, basic LHH/CD concept for a power plant-level plasma could be tested on any machine.

Table 3.4. Fueling and pumping

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
Fueling F1. Steady-state cryogenic fueling - continuous extrusion system F2. High-speed pellet injection from multiple locations - low and high field sides F3. Tritium-compatible pellet fueling Pumping P1. Steady-state cryogenic vacuum pumping system - regeneration in isolated subsections P2. Helium pumping - compatibility with solid or liquid walls	Fueling High-speed pellet test stand (F1, F2) - tritium compatible - mass flow Pumping Large-scale cryogenic vacuum pumping test facility (P1) - tritium compatible Large-scale pumping test facility compatible with solid or liquid walls (P1, P2) - thermal, mechanical loads	IGNITOR Fueling Significant: Issues F1, F2, F3 Pumping: None - low field side pellet injection only - no helium pumping FIRE Fueling Major: Issues F1, F2, F3 Pumping Significant: Issues P1, P2 - low duty cycle ITER Fueling Major: Issues F1, F2, F3 Pumping Major: Issue P1 Significant: Issue P2 - high duty cycle - helium pumping for solid wall only

Table 3.5. Vacuum vessel and remote handling

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
Vacuum Vessel VV1. Development of design code - regulatory acceptance - VV as primary safety barrier VV2. Remote cutting, welding, inspection - for assembly/disassembly joints - for each specific geometry/material VV3. Close stabilizing coils/structures - MHD control in AT operation - active coils, radiation resistant - passive structures bonded to vessel - disruption forces, integral cooling Remote Handling RH1. In-vessel handling and inspection - handling, control, precise positioning - in-vessel, port-mounted components RH2. Ex-vessel maintenance - component transfer for maintenance - cask-based with double seal doors RH3. Hot cell repair/refurbishment - in-vessel, port-mounted components	Vacuum Vessel No generic facilities are envisioned Testing specific to a design code (VV1) DT confinement experiments (VV2, VV3) - specific to each individual design Remote Handling Generic RH facility (RH1) - manipulators, welding heads, mock-ups Device-specific RH facilities (RH1 - 3) - included in device R&D process - test RH operations prior to deployment	IGNITOR Vacuum Vessel Significant: Issue VV2 (to be determined) None: Issues VV1. VV3 - may use existing code Remote Handling None: Issue RH3 Significant: Issues RH1, RH2 - RH limited FIRE Vacuum Vessel None: Issue VV1 (may use existing code) Major: Issues VV2, VV3 Remote Handling Major: Issues RH1, RH2, RH3 - RH similar to ITER but with smaller components ITER Vacuum Vessel Major: Issues VV1, VV2 - will probably need new/revised safety code None: Issue VV3 Remote Handling Major: Issues RH1, RH2, RH3

Table 3.6. Safety and tritium

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
Safety S1. Avoidance of public evacuation even in worst case accidents - radioactive materials, dust, PFCs - energy sources for mobilization - tritium retention at high throughput - development of integrated codes for comprehensive safety analysis S2. Minimization of radioactive waste - development of design criteria - advanced materials/coolants - safety aspects of liquid walls - recyle/reuse of fusion materials Tritium T1. High-throughput tritium processing - isotope separation, HTO processing - 1-kg-class inventory control/safety - cryopumps, rapid hydride beds - purification, waste handling - permeation in heat exchanger - activation products effects on processing equipment - accountability and safeguards T2. Tritium breeding and self-sufficiency - recovery from breeding blankets - advanced blankets, liquid walls - external tritium supply availability	Safety Small–scale R&D facilities (S1, S2) - validate analysis/computer codes - tokamak dust, solid PFC materials - test advanced materials/coolants - coordinated through IEA program ITER-class facility (S1) - integrated power plant-like fusion system - validate some key safety assumptions in low-power operation - validate comprehensive safety analysis (A CTF/VNS could possibly fulfill much of the ITER role in safety analysis validation) Tritium Test facilities - scale of TSTA (T1,T2) - via international collaboration - tritium accountability, online inventory measurement/control - test materials interactions, advanced blanket materials, Flibe, liquid Li ITER-class facility (T1) - quasi-continuous, high-throughput, closed-cycle tritium processing - provision for blanket test modules	Safety IGNITOR: Essentially no contribution FIRE: Essentially no contribution toward the licensing of a DEMO, but useful experience with tritium at high throughput and burn, and tritium retention in PFCs. ITER: Major (Issue S1) - high tritium inventory/throughput - power plant-like machine configuration - high duty-factor, high availability - would streamline licensing process for DEMO Tritium IGNITOR & FIRE: Essentially no contribution to tritium technology development, since present-day tritium systems would suffice. ITER: Major (Issue T1) - 1-kg inventory - quasi-continuous, closed system with < 1 hour cycle time - breeding in blanket test modules

Table 3.7. Materials

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
Radiation resistant materials 1. Vanadium (V-Cr-Ti alloys) - insulator for Li coolant - ductile/brittle transition - welding, large-scale construction 2. Ferritic steels (Fe-Cr-W/V0 - acceptability in MFE devices - radiation hardening/He production effects on fracture 3. Silicon Carbide (SiC/SiC) - radiation damage resistance - radiation effects on thermal cond. - joining and sealing 4. Qualification of selected material(s) - maximize performance and operating window - establish production, fabrication, joining, chemical compatibility and mechanical properties - establish radiation resistance/14MeV - provide materials database for design, licensing, construction and operation of a power power plant Other materials 5. Establish radiation tolerances - PFCs, heat sinks, diagnostics	Required testing parameters Neutron flux = 3 MW/m^2 Surface heat flux = 20% neutron flux Neutron fluence = 15 MW.yr/m^2 Displacements = 30 dpa/yr Irradiation tests in fission power plants - flux, fluence too low - neutron spectrum incorrect - near-term partial contributions to Issues 1, 2, 3, 5 Dedicated Fusion Materials Irradiation Test Facility (1, 2, 3, 4) IFMIF: Neutron flux [n/(s.cm^2)] ˜ 4x10^{14} - 10^{15} Neutron power flux (MW/m^2) ˜ 3 – 8 Displacements (dpa/FPY) ˜ 20 – 55 Hydrogen prod (appm/FPY) ˜ 1000 – 2500 Helium prod (appm/FPY) ˜ 250 –600 Hydrogen/dpa ratio (appm/dpa ˜ 35 – 50 Helium/dpa ratio (appm/dpa) ˜ 9.5 – 12.5 Hydrogen/dpa, helium/dpa ratios similar to fusion power plant, displacement production up to 2-3 times higher	Radiation resistant materials (Issues 1 – 4) IGNITOR: None - fluence negligible FIRE: None - fluence negligible ITER: slight - fluence (0.3 MW.yr/m^2, 3 dpa) too small for radiation damage effects Other materials (Issue 5) ITER: Neutron irradiation effects occurring at low fluence (= 3 dpa) IGNITOR, FIRE: Irradiation effects requiring high flux, negligible fluence - ceramic insulators - optical materials - polymers - diagnostic components - copper alloys for heat sinks, PFC substrates

Table 3.8. Blankets

Technology Development Issues	Facility Needs (Issue #)	Contributions from BP Experiments
1. Tritium breeding and self-sufficiency - nuclear data and codes - fuel cycle 2. Blanket tritium recovery, inventory and containment 3. Energy recovery thermal hydraulics and mechanics efficient power conversion 4. Materials compatibility and interactions 5. Component lifetime and reliability	Neutron source facilities - *e.g.*, FNS Tritium processing facilities - *e.g.*, TSTA Thermofluid facilities - fluid dynamics - thermomechanics High-fluence neutron irradiation facilities - *e.g.*, IFMIF Integrated test facilities - *e.g.*, CTF/VNS - high-volume, high fluence	IGNITOR - no breeding blanket - no active first-wall cooling - no access for test modules FIRE - no breeding blanket - pulse length sufficient for first wall thermal equilibrium - pulse length too short for blanket thermal equilibrium - limited access for test modules ITER - breeding blanket - pulse length sufficient for first wall and blanket thermal equilibrium - superior access for test modules - neutron fluence adequate for some mechanical property tests, but too low (3 dpa) for neutron damage test

4. Power Plant Plasma Regimes

Progress in plasma physics during the past decade has been remarkable. For tokamaks, our vision of tokamak power plants, costly and large devices operating in the pulsed mode, is replaced with high-performance, advanced tokamak modes of operation. While experimental database for advanced tokamak mode is not sufficiently mature to be based as the basis of design of a BPX, tremendous progress has been made. It is quite conceivable that the advanced tokamak mode database will be mature enough at the time of operation of BPX that they can be thoroughly explored in burning plasmas. As such, flexibility to explore advanced tokamak modes represents an attractive feature and a discriminator among BPXs.

Contribution of high-performance advanced tokamak modes to power plant attractiveness has been explored by conceptual power plant studies. Results from these studies can be used to identify physics regimes that should be explored in a BPX.

Steady-state first-stability

In the late 1980's, operation at high bootstrap current fraction as the approach to steady-state operation was proposed by ARIES-I [5] and SSTR [6] studies simultaneously and independently. In order to reduce the current-drive power, the plasma current is reduced while the bootstrap fraction is maximized. In the first-stability regime, this can be accomplished by operating with a moderately high plasma aspect ratio ($A = 1/\varepsilon \sim 4.5$) and low plasma current ($I \sim 10$ MA) at a relatively high poloidal beta ($\varepsilon\beta_p \sim 0.6$). For a conventional first stability configuration (discharges stable to kink modes without a conducting wall), detailed MHD and current drive analysis have showed that a bootstrap fraction of ~60% can be achieved but with a $\beta_N \sim 3$ (and a low plasma $\beta \sim 2\%$). Most of the driven current located near the magnetic axis, requiring a current-drive power of about ~100-200 MW delivered to the plasma. There is ample experimental database for this regime, however, operation in discharges with durations longer than the current diffusion time as well demonstration in a burning plasma are needed.

Pulsed-plasma Operation

There have been no studies of pulsed-plasma tokamak in last 15 years with the exception of Pulsar study performed by the ARIES Team during 1992-1993 [7]. A pulsed-tokamak power plant should operate with a constant thermal (and electrical power) output as the rate of change of temperature of thermal power to the thermal conversion system is very limited (*i.e.,* a few ^{o}C/min). Earlier studies have all concluded that pulsed-operation lead to large and expensive power plants due to high cost of thermal storage between pulses. Pulsar design featured an innovative thermal storage system. It showed that with minimal additional cost, shield could be used as thermal energy storage (for a few 100 seconds) by careful splitting and rerouting of the coolant [8]. As such, the remaining issues with a pulsed-tokamak power plant are: 1) high cost of OH transformer, and 3) cyclic fatigue of various components.

Energetic of a pulsed-tokamak power plant requires that the burn time to be much longer the dwell time (the time to start the plasma and achieve a steady burn, the time to shutdown the plasma, and the time between pulses to reset the OH transformer and prepare the plasma chamber for the next pulse). This requirement leads to burn times of order ~1-4 hours. Longer burn time is not optimum because of increased cost of the OH system. The large size and cost of the OH transformer dictate the size of the tokamak and the optimization direction *i.e.,* low current (to minimize V-s of OH transformer) and high aspect ratio (to provide space for the OH transformer).

A comparison of major parameters of a 1000-MWe steady state and pulsed power plants using *same* physics and technology basis is shown in Table 4.2 [9]. Our results indicate that both pulsed-plasma and steady-state first-stability devices optimize in the same physics regime: low current and moderate bootstrap current fraction. Because of the long burn time in a pulsed-plasma power plant, plasma is essentially in steady state. As such, physics needs of pulsed-plasma and steady state first-stability devices are identical (the only difference, physics of non-inductive current drive, is well established). As the low recirculating power fraction of pulsed-plasma operation is more than offset by the lower power density, larger size, and the expensive PF system, pulsed power plants tend to be more expensive than steady-state ones.

Table 4.2

Major parameters of 1000-MWe steady-state (ARIES-I’) and pulsed-plasma (Pulsar)
1st stability power plants (A = 4, κ =1.8)

	Steady State	**Pulsed**[(a)]
Major radius (m)	8	8.7
Plasma current (MA)	12.6	15
Bootstrap current fraction	0.57	0.34
β_N	2.9	2.7
β	2.0	2.5
Peak field on coil (T)	16	13
Field on-axis (T)	9	7.5
Ave. wall load (MW/m^2)	1.5	1.2
Recirculating power fraction	0.29	0.06
COE (c/kWh)	10	13

(a) A pulsed-tokamak with no bootstrap assist would be ~1.3-1.5 times more costly and larger than Pulsar (~3-4 times of the cost goals of Table 2.1).

The Pulsar design of Table 4.2 uses bootstrap assist to reduce the V-s requirement of the OH transformer. A pulsed-tokamak with no bootstrap assist would be ~1.3-1.5 times more costly and larger than Pulsar (~3-4 times of the cost goals of Table 2.1). While such a pulsed-plasma power plant is technically feasible and closest to present tokamak experimental database, it is improbable that any technological advances could make such a system competitive with other sources of energy.

High Performance Fusion Plasmas

Starting from a steady-state, first-stability device, power plant economics can be improved by increasing fusion power density and decreasing the recirculating power fraction. It should be noted that economics improvement with increasing fusion power density "saturates" after a certain limit. At low power density, any reduction in plasmas size (increase in power density and wall loading) proportionally decreases the volume of fusion core (blanket/shield/coils) that surrounds the plasma (and the system cost). However, when plasma size is comparable and/or smaller than the thickness of blanket and shield, the volume of fusion core (and its cost) does not change appreciably with reduced plasma size (increased power density). For 1000-MWe power plants, economic improvements with increased wall loading saturates at an average neutron wall load of ~4-5 MW/m^2. As a reference, a first-stability steady-state device with a 16-T magnet technology achieves a neutron wall loading of ~1.5 MW/m^2.

High-field magnets can be used to increase the fusion power density as is shown in Table 4.3. (ARIES-I featured a 19-T cryogenic TF system.) Because fusion power density scales as β^2B^4, the impact of increased toroidal field is quite dramatic. The increase in fusion power density leads to a substantially smaller device and a slightly lower current-drive power, both factors combine to help improve power plant economics.

Alternatively, one could operate in reversed-shear regime. The benefits of this configuration are that it achieves both high β_N and β, it obtains large bootstrap fractions with very good current profile alignment, and features an internal transport barrier necessary to sustain the peaked pressure profiles that is consistent with the high β and high bootstrap current. The negative central magnetic shear is responsible for stability to ballooning modes. A conducting wall, however, is necessary for stabilization of external kink modes – and the resistive-wall modes should be stabilized with plasma rotation and/or feedback coils.

Reversed-shear regime of operation was analyzed in ARIES-RS [10], ARIES-AT [11], A-SSTR2 [12] and CREST [13] studies (see Table 4.3). In both ARIES studies, a large database of stable MHD equilibria was generated and their non-inductive current drive needs were calculated. This database was then used by the ARIES Systems Code to arrive at the optimum power plant configuration. Analyses showed that to zeroth order, the cost of electricity is insensitive to the plasma aspect ratio in the range of 2.5 to 4 (lower plasma β at the higher A is compensated by higher toroidal-field strength on axis and lower current-drive power). An aspect ratio of 4 was chosen for both ARIES-RS and ARIES-AT based on engineering considerations. ARIES-RS design achieved a plasma $\beta = 5\%$ ($\beta_N = 4.8$) and a bootstrap current fraction of ~88%. Plasma profiles were better optimized in ARIES-AT ($\beta = 9.2\%$, $\beta_N = 5.4$), such that while the bootstrap fraction was only increased slightly in ARIES-AT to 0.91, the current-drive power was reduced by a factor of two. The large difference between β values in the two designs is due to the higher plasma elongation of ARIES-AT (passive vertical stabilization shells, located behind the blanket, are relatively closer to the plasma because of "thinner" ARIES-AT blanket). The increased plasma β in ARIES-AT is used to reduce the toroidal field requirement instead of increasing power density and reducing system size.

Compared with ARIES design, A-SSTR2 [12] utilizes a less aggressive reversed-shear regime

(β_N = 4.2) and its lower β value is compensated by advanced technologies (*e.g.,* operation with 23 T magnets) while CREST [13] has explored a more aggressive physics together with conservative technologies (*e.g.,* water-cooled blanket with low thermal efficiency).

High-leverage directions for BPXs

Intercomparison of these design studies provides a wealth of information on the potential of fusion as an attractive and sustainable energy source and directions for fusion development. Major conclusions are:

1) Assuming same physics (first stability, 40% to 60% bootstrap current fraction) and same technology extrapolations, a pulsed-plasma power plant is inferior to a steady-state. The relative difference in cost and size will remain (or widens) as more advanced technologies can be incorporated.

2) A pulsed-tokamak with no bootstrap assist would be ~1.3-1.5 times more costly and larger than Pulsar (~3-4 times of the cost goals of Table 2.1). While such a pulsed-plasma power plant is technically feasible and closest to present tokamak experimental database, it is improbable that any technological advances could make such a system competitive with other sources of energy.

3) As a whole, development of advanced tokamak modes (i.e., steady-operation with >60% bootstrap fraction) is necessary for an acceptable tokamak-based fusion power plant.

4) The advanced tokamak mode closest to present experimental achievement is a steady state, first stability plasma. A fusion power plant based on first-stability steady-state plasma together with advanced technologies, specifically high-field magnets such as ARIES-I, would have acceptable performance.

5) Advanced tokamak modes base on reversed shear together with advanced technologies lead to attractive power plants that are projected to meet fusion power requirements as stated in Table 2.1. At “lower” range of possible β_N, high-field magnets should be used to achieve a reasonable power density (such as ASTTR-2), while at the higher range of β_N, the high performance of the plasma lead to a lower demand on technology extrapolation.

Table 4.3
Major parameters of several advanced tokamak power plants

	First Stability			**Reverse-Shear**				
	EU Mod-A*	**ARIES-I'**	**High-field: ARIES-I**	**ASTTR-2**	**ARIES-RS**	**ARIES-AT**	**CREST**	**EU-Mod D***
Major radius (m)	9.8	8.0	6.75	6.2	5.5	5.2	5.4	6.1
Minor radius (m)	3.3	2.0	1.5	1.5	1.4	1.3	1.6	2
Plasma elongation, κ	1.7	1.8	1.8	1.8	1.7	1.9	2	1.9
β (β_N)	4.8% (3.4)	2% (2.9)	2% (3.0)	3%(4.2)	5% (4.8)	9.2% (5.4)	5% (5.5)	5.6% (4.5)
Peak field at the coil (T)	12.9	16	19	23	16	11.5	12.5	13.4
On-axis field (T)	7.3	9.0	11	11	8	5.8	5.6	5.6
ITER89-P multiplier		1.7	1.9	2.7	2.3	2.0	3.2	
Plasma current (MA)	33.5	12.6	10	12	11.3	13	12	14
Bootstrap current fraction	0.36	0.57	0.57	0.80	0.88	0.91	0.83	0.76
Current-driver power (MW)	265	237	202	60	80	35	97	71
Recirculating power fraction		0.29	0.28		0.17	0.14		
Current drive efficiency (A/W)	0.081	0.023	0.021	0.040	0.017	0.033	0.021	0.047
Fusion Power (MW)	5,500			4,000	2,170		3,000	2,500
Avg. wall load (MW/m^2)	2.3	1.5	2.5	8 (peak)	4	3.3	6.5 (peak)	
Structural Material	Ferritic Steel	V alloy	SiC	SiC	V alloy	SiC	Ferritic Steel	SiC
Coolant	Water	Li	He	He	Li	LiPb	Water	LiPb
Breeder/multiplier	LiPb	Li	LiZrO/Be		Li	LiPb		LiPb
Thermal efficiency	0.31	0.46	0.49		0.46	0.59		0.61
Electric Power (MWe)	1,500	1,000	1,000	2,000	1,000	1,000	1,000	1,500
Cost of Electricity (c/kWh)	-	10	8.2	-	7.5	5	-	-

* Ref. [14]

5. Innovative Confinement Concepts (ICCs) and the Magnetic Portfolio

The U.S. Fusion Energy Sciences program has adopted a multiple path strategy for optimizing fusion energy development. Central to this strategy is the “portfolio approach”, where multiple plasma confinement configurations advance, in parallel, through varying stages of development. The portfolio approach provides an excellent vehicle for program innovation and a means for broadening the scientific and technical basis for fusion energy with a view to developing the best fusion energy sources. Its success, however, is very dependent on the coherent integration of the portfolio’s scientific and technical contributions to fusion energy development. This integration must be pursued at all stages of a concept’s development.

The fusion development stages have been discussed in other reports and are summarized here for completeness. In order of increasing technical maturity, the first three stages are “Concept Exploration”, “Proof-of-Principle”, and “Performance Extension”. Concept Exploration experiments are relatively low-cost experiments that investigate the basic plasma characteristics of a confinement concept. The Proof-of-Principle stage is intended to develop an integrated understanding of the basic science of a concept. Performance Extension programs explore the physics of the concept at or near fusion-relevant regimes.

Success in these first three stages should then, in principle, lead to the “Fusion Energy Development” and “Fusion Energy Demonstration” stages. The Fusion energy Development stage, such as a burning plasma experiment (BPX), is intended to develop the technical basis for advancing a concept to the power plant level in a fusion environment. However, the large cost and development time associated with these last two stages will most likely preclude pursuing concepts in parallel. Hence, it is likely that there will only be one BPX class facility in the near future based on the tokamak. The Fusion Energy Demonstration (DEMO) step that follows the BPX could have better power-plant attributes than a standard tokamak, by taking advantage of improvements that would be available from a mature portfolio. To make this possible, the portfolio must continue to advance in both maturity and breadth. In addition, the BPX must be designed and planned to deliver generic benefits, and a reliable predictive capability must be developed based on understanding and tested models that span the range of configurations.

The requirement for a mature portfolio can be satisfied by continuing to follow the development strategy established in recent years. Configurations that are now at the proof-of-principle stage, namely the spherical torus (ST), compact stellarator (CS), and reversed-field pinch (RFP) are closely related to the tokamak and in the next 5-15 years are natural candidates for promotion to performance extension, joining the advanced tokamak (AT) and the stellarator (S). A substantial performance extension knowledge base for these configurations can be made available by the time DEMO decisions need to be made, about 25-30 years from now. In the same period, some configurations now at the exploratory stage will most likely advance to proof-of-principle, and the opportunity to introduce new ideas for study at the concept exploration stage will be continuously maintained. This strategy provides opportunity for configurations that are less closely related to the tokamak, but have the potential for more dramatic improvements, to contribute to decisions on fusion development beyond the burning plasma experiment.

The requirement for coherent integration across elements in the fusion program drives each element to develop a level of understanding and predictive capability such that knowledge transfer across magnetic configurations becomes possible. In this sense, developing a predictive capability for ultimately designing the best fusion power plant becomes the integrating principle across program elements as illustrated in Figure 5.1. For example, knowledge-based integration allows for "transferring" scientific discoveries from innovative confinement concepts (ICCs) to tokamaks with the goal of improved tokamak performance. Conversely, a tokamak BPX that had the flexibility in design, operation, and diagnostics to address a broad range of physics and technology issues could impact the development path of ICCs as well. There exists commonality across the portfolio in major development issues such as macrostability, transport and turbulence, wave-particle interactions, plasma-material interactions and boundary physics. Incorporating this broad physics based in our predictive tools will provide the capability to transfer knowledge across concepts.

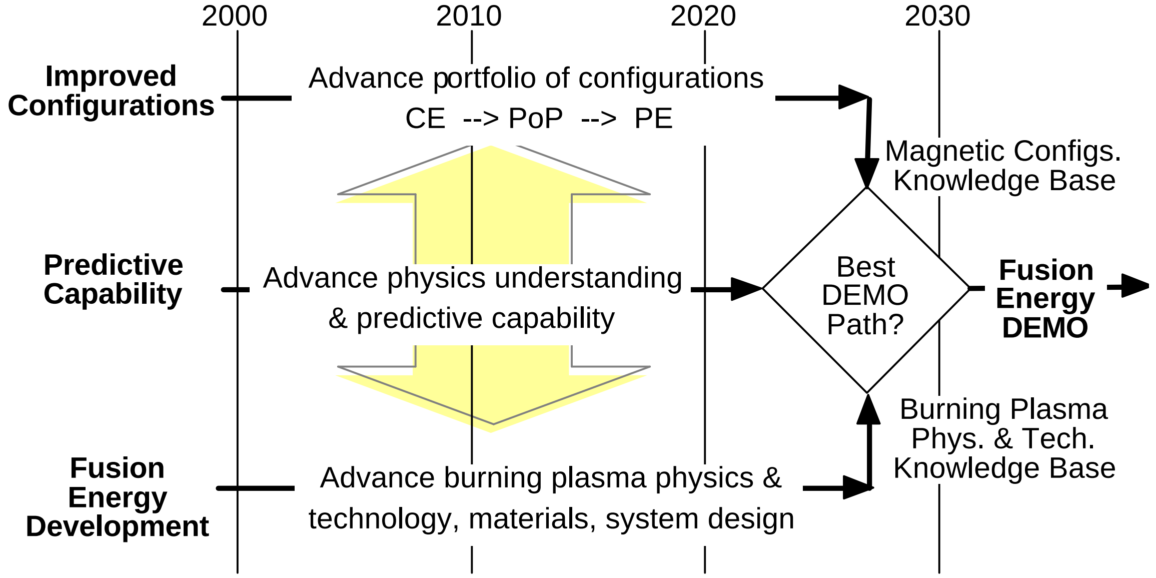

Fig. 5.1. Program for Developing a Practical Magnetic Fusion Energy

From the portfolio perspective, the role of a tokamak BPX is to address, in as broad a way as possible, burning plasma science (i.e. alpha particle physics) and technology (i.e. superconducting magnets, power and particle exhaust, fueling, tritium, remote maintenance, etc.). In addition, the BPX will afford the opportunity to study effects related to device scale and performance such as the ratio of plasma size to gyroradius, wall loading, and pulse length. The degree of transferability of BPX physics understanding to other ICC concepts is both concept specific and issue specific. For example, if tokamaks and quasi-symmetric stellarators have a high degree of commonality in their physics, then the understanding of burning-plasma physics effects, obtained in a tokamak BPX, should transfer readily to stellarators for integration with the three-dimensional plasma effects. Similar transferability is expected for the spherical torus for integration with the effects of order-unity ? and strong shaping. With respect to the reversed field pinch (RFP), there is also the possibility for commonality in basic physics. Recent developments in reducing magnetic-driven transport in RFPs, by means of profile control, enables the examination of limiting transport mechanisms and their relation to those seen on tokamaks, spherical tori, and stellarators. If underlying RFP transport is similar, then the predictive understanding developed for the full compliment of toroidal plasma research, including a tokamak BPX, will impact the RFP development path as well.

A burning plasma experiment can make substantial contributions to the development of magnetic fusion energy, if properly planned and executed. Although it will use a tokamak to confine the plasma, the BPX needs to support the goal of improving the vision of a magnetic fusion power plant, so it must deliver benefits that are generic to a range of magnetic fusion concepts. A burning plasma experiment can take a major step in the integration of fusion technologies in a realistic environment. The production of hundreds of megawatts of fusion power for hundreds of seconds from a high-gain plasma will be a success for plasma physics models and will demonstrate substantial progress in understanding of the design, construction, and operation of a major fusion system. Beyond that, achieving levels of availability approaching those required for a fusion power plant would demonstrate that magnetic fusion could be practical. Accomplishing these objectives in a burning plasma experiment will involve advances over the next twenty-five years or so that are generic to a range of magnetic fusion concepts. Examples include MHD modes driven by energetic alphas, neoclassical tearing modes at large ratio of gyroradius to system size, steady-state heat removal and helium exhaust, magnetics, diagnostics, heating and fueling, and maintenance. Thus, the value of a tokamak burning plasma experiment to the goal of attractive fusion will depend on how successful we are in generalizing and integrating the knowledge gained from the BPX to other concepts. In particular, the integration of the knowledge base from a BPX with the portfolio of ICC experiments up to the Performance Extension stage will be required to achieve the predictive capabilities needed to determine the designs of the best fusion energy sources for power production.

In conclusion, with a well planned and integrated program, there is an excellent chance of advancing the physics and technology of fusion energy as well as substantially improving the vision of magnetic fusion energy. Such a program will maximize the value of a tokamak burning plasma experiment and the opportunity for much more attractive next steps thereafter. The key program requirements are:

1. Developing physics solutions to improved power plant attractiveness by advancing a portfolio of concepts through their development stages based on merit.
2. A burning plasma experiment aimed at developing a deep understanding of the physics and technology of burning plasmas. It must have good flexibility, capable diagnostics, and a strong theory and modeling component.
3. Advancing the understanding and predictive capability for fusion plasma physics in a way that integrates the portfolio, such that knowledge gained from one concept can be readily transferred to others for the ultimate purpose of developing the best fusion energy system.

6. Development Path Scenarios

The development path to realize fusion as a practical energy source must include four essential elements:

1) Fundamental understanding of the underlying science and technology;
2) Plasma physics research in a burning plasma experiment;
3) Configuration optimization such as high performance, steady-state operation;
4) Development of low-activation materials and fusion technologies

Burning plasma physics and configuration optimization: A diversified and integrated portfolio consisting of burning plasma experiment(s), steady-state DD tokamak experiments, ICCs, and theory/simulation is needed to develop the necessary predictive capability in burning plasma physics and high-performance state operation and concept operation. The BPX should be flexible and well diagnosed in order to provide fundamental understanding and physics and technology data for the entire toroidal concept portfolio.

Plasma Support Technologies: A strong base program in plasma support technologies (fueling, magnets, heating, PFC) including experiments on test stands is necessary to develop advanced technologies necessary for power plants. Experience on present and future high performance and steady state device as well as the BPX will provide a wealth data on individual technologies. Among the proposed BPX experiments, ITER will provide valuable data on integration of power-plant relevant plasma support technologies.

Low-activation material and fusion power technologies: All scenarios considered require development of low activation material and fusion power technologies for integration at a subsequent device to BPX. Fusion power technologies are in their infancy and are probably a pace setting element of fusion development. Development of fusion power technologies require:

1) A strong base program including testing of components in non-nuclear environment as well as fission reactors.
2) Material program including an intense neutron source to develop and qualify low-activation material. International Fusion material Irradiation Facility (IFMIF) is an example of such a material test facility and has been included in fusion development plan worldwide.
3) A Component Test Facility (CTF) which is sometimes referred to as a volume neutron source (VNS) for integration and test of power technologies in fusion environment with a high duty factor [13]. Such a device should test and integrate fusion power technologies under proto-typical power and neutron flux and fluence and should address reliability of components in a power-plant environment.

There is a strong consensus in the international fusion scientific community that the tokamak is technically ready for the steps to burning plasma physics and steady-state operation. There is, however, a range of opinions (hence different pathways) about the most cost-effective and technically sound approach. Development paths featuring FIRE, ITER, and IGNITOR all require a strong base program, test stands, and companion experiments and, therefore, fit in a Portfolio approach to fusion development. Fusion development paths based on FIRE, ITER, and IGNITOR differ on the degree of development and integration of the four fusion challenges in the next step device and to the degree that these challenges are deferred. The contributions of proposed BPXs, ITER, FIRE, and IGNITOR, on the fusion development strategy are described in sections 6.1 to 6.3, respectively. Table 6.1 summarizes the interplay of integrate and optimize versus optimize and integrate approaches of these scenarios. The role of ICCs in the fusion development path is discussed in Section 6.4.

Table 6.1.
Principal advantages and disadvantages of different development scenarios

Development path based on	Advantages	Disadvantages
ITER-FEAT-class BPX	Early exploration and optimization of integrated burning plasma, steady state (AT) operation, and plasma support technologies. Minimizes number of steps (and time) to tokamak-based fusion power.	Higher cost facility investment.
FIRE-class BPX	Early exploration of integrated burning plasma and steady-state (AT) operation. Reduces initial facility investment costs and allows optimization of experiments for separable missions. Provides further optimization before integration steps, allowing perhaps a more advanced and/or less costly integration step to follow.	A follow-up integration step is necessary, may lead to a longer development path.
IGNITOR-class BPX	Early demonstration of an important fusion milestone, burning plasmas. Low initial facility investment cost.	Require an ITER-FEAT-class or a FIRE-class scenario to follow.

6.1. Fusion development scenario based on ITER-class burning plasma experiment

The logic diagram of fusion development scenario with ITER as the major burning plasma device is shown in Figure 6.1. The elements of this development path are described below.

Burning plasma physics and configuration optimization

It is highly unlikely that an ITER-class experiment would be the only large tokamak experiment in the world. National or regional programs will include performance-extension tokamak devices. Most probably, these devices will explore steady-state advanced tokamak physics. These devices are needed to ensure continuation and growth of national expertise and capabilities. More importantly, physics investigations on these performance-extension devices will allow optimum utilization of ITER-class experiment. Smaller devices would allow thorough investigation of individual physics phenomena and act as a test bed for ideas, which can be tested in an integrated manner in ITER. As such, an international tokamak research program centered around ITER and including these national performance-extension devices have the highest chance of success in thorough examination of burning plasma physics in advanced tokamak modes.

Plasma Support Technologies

Because of its size, its relatively high duty factor, and its neutron flux and fluence, will provide valuable data on integration of power-plant relevant plasma support technologies. A strong base program in plasma support technologies (fueling, magnets, heating, PFC) including experiments on test stands is still necessary to develop advanced technologies necessary for power plants.

Low-Activation Material and Fusion Power Technologies

A unique aspect of an ITER-class burning plasma is the capability for limited testing of fusion power technologies. However, because of the low base-line fluence of 0.3 MW.yr/m^2 and relatively low neutron flux, there would be a high risk to proceed to an electricity producing device solely based on ITER testing program. As described above, a strong base program, an intense neutron source facility and a CTF/VNS is necessary before proceeding with the DEMO. ITER capability in testing fusion power technologies as well as the ITER experience on integration and operation of a variety of fusion technologies are valuable to CTF/VNS operation.

Decision Point

Successful completion of ITER experimental program (demonstration of high-performance AT burning plasma) will allow tokamak concept to move to fusion power demonstration (DEMO). Here DEMO is defined as a device which incorporates all physics and technologies necessary for an attractive commercial power plant. Alternatively, the tokamak concept may be replaced by an emerging but promising alternative concept. A “success-oriented” time table for fusion development in such a scenario is given in Figure 6.2.

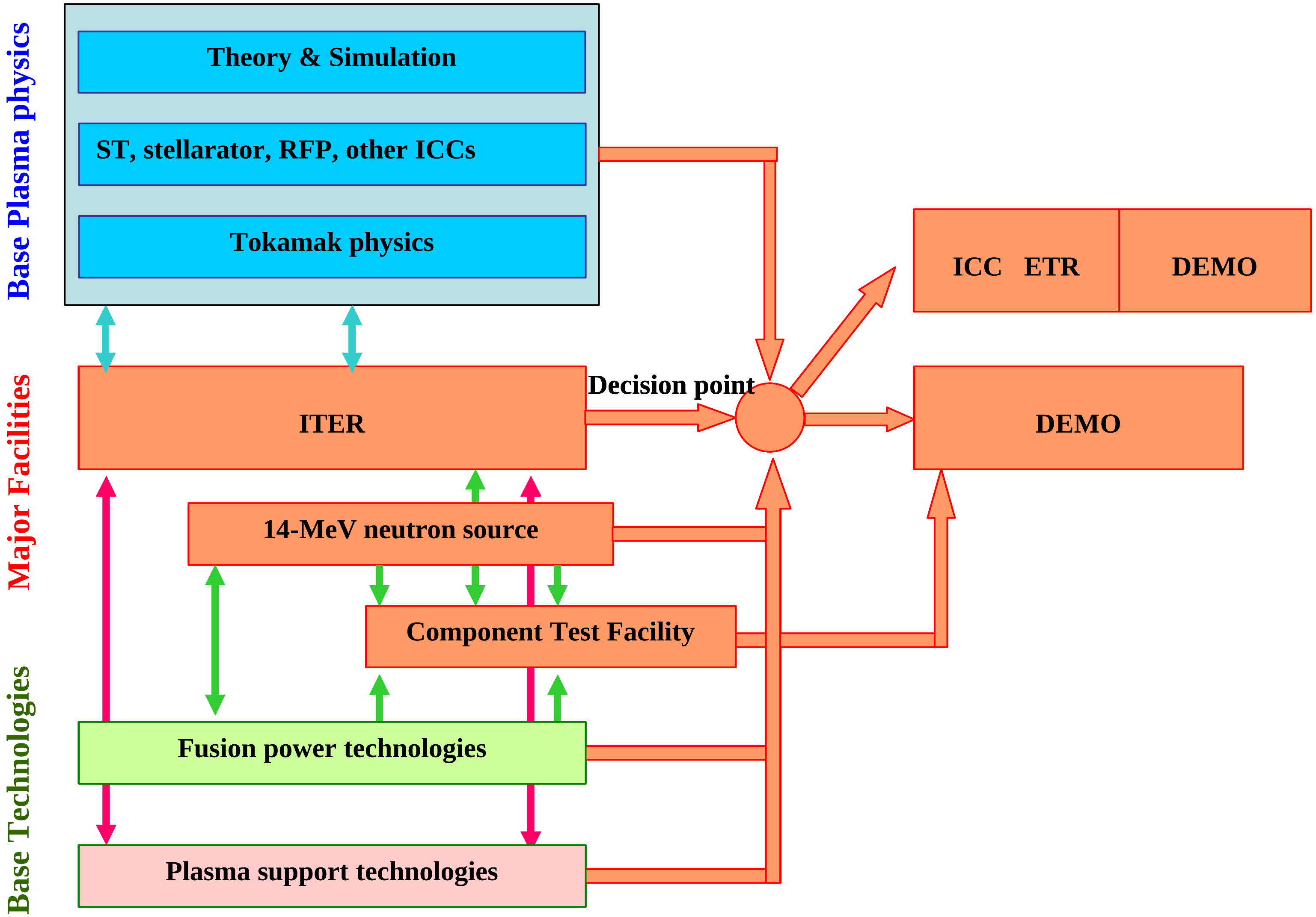

Fig 6.1. Schematic of development path based on ITER-class burning plasma experiment.

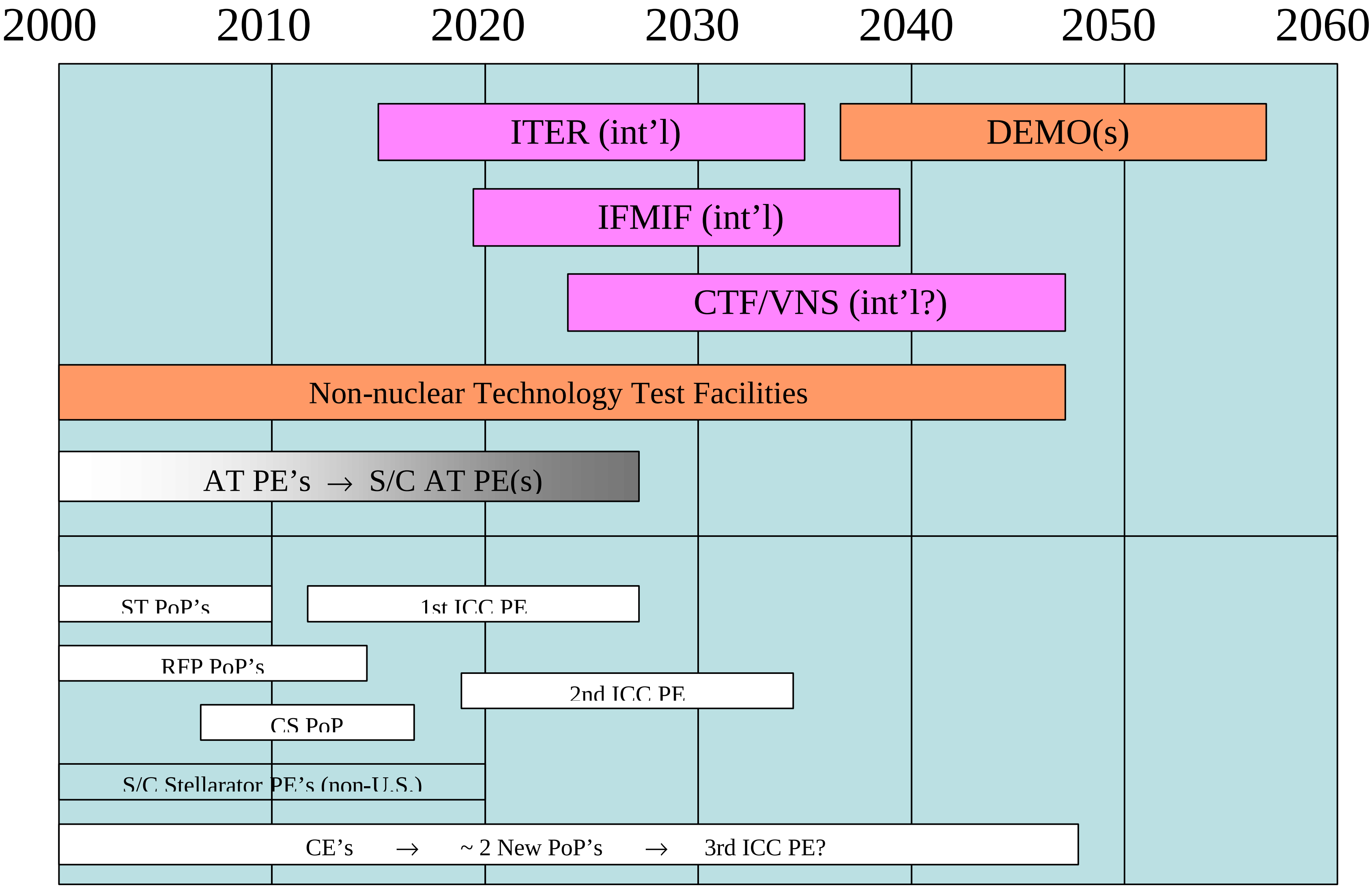

Fig 6.2. A "success-oriented" time table for fusion development scenario with ITER. Boxes indicate facility operation time frame.

An ITER-class BPX allows leapfrog in fusion development path by combination three areas of burning plasma physics, advanced tokamak modes, and plasma support technologies. Assuming successful outcome (demonstration of high-performance AT burning plasma), it would lead to the shortest development time for fusion.

Issues and Responses

Several issues with regard to proceeding with ITER-based development path scenario were identified and discussed during the fusion summer study. These issues and responses are given below:

1) An ITER strategy would have larger initial cost.

> Ultimately an ITER-class machine must be successfully built and operated before DEMO, Therefore, the cost is not reduced, only postponed.

2) ITER strategy is risky. It must confront all of the major next-step physics/technology issues. In addition, modification and upgrade would be costly and may prohibit test of some ideas.

> A single device has a higher risk compared to a sequence of smaller steps but produces larger opportunities in examining advanced tokamak burning plasmas. Risk should be balanced against benefits. Risk can be minimized by aggressive, focussed R&D and maintaining strong base program, including tokamaks, ICCs and theory/simulation.

3) There are a large number of uncertainties with an international device. Agreements on siting, cost-sharing, project management, *etc.* are required. Key decisions need to be made by negotiation leading to consensus.

> a) Fusion has had a long and successful history of international collaboration with obvious benefits to all partners.
> b) By joining an international consortium to build a BPX, we can take a more aggressive step, saving both development time and money.
> c) Joining an international consortium to build a BPX would add funding stability to both the construction and operation phases.
> d) Most of the important design decisions for ITER have already been made. In fact, the US had huge input to the process.
> e) Physics has no respect for national sovereignty. The operating program will be structured by the need to extract the physics rather than by parochial national interests.
> f) This is not to minimize the problem, only to point out that the international approach can be made to work. Early participation in negotiations is key.

6.2. Fusion development scenario based on FIRE-class burning plasma experiment (Diversified International Portfolio Pathway)

The goal of the Diversified International Portfolio Based pathway is to provide the technical basis for the ARIES vision. The ARIES studies carried out by a national US team over the past decade have studied a range of potential tokamak fusion power plants ranging from those based on today's physics and technology to advanced systems based on expected innovations in physics and technology. The ARIES-RS and AT design studies have identified the key characteristics needed for a magnetic fusion power plant to be economically competitive and have an environmental impact that is benign in terms of safety and waste:

- Advanced tokamak physics – high β ($\beta_N > 4$), steady-state (high bootstrap current fraction)
- Burning plasma physics – high Q, controlled AT modes, ash removal and stable to TAEs, etc
- Advanced technology – HTS magnets, high temperature thermal conversion, etc
- Advanced materials and fusion power technologies – low activation, neutron resistant

Each of these desired characteristics is a significant advance beyond our present capability, and represents a major scientific and technical challenge. Some of these challenges can be addressed in stand-alone facilities while others are coupled and need to be addressed in a more integrated facility. Many of these technical issues are expected to be resolved on differing time scales. A key strategic question is the sequence and scale at which to do the innovation and integration of these key characteristics. The response to this question defines different pathways.

The Diversified International Portfolio Pathway seeks to address the physics and technology issues and develop the required innovations at the earliest time and the smallest scale (lowest cost). The overall international program would be carried out on several complementary facilities distributed among the major parties; each facility would be optimized to address critical fusion science and technology issues in an integrated international program. This type of multi-machine or diversified portfolio program strategy has been described previously by Rebut [14], PCAST [15], Meade [16] and Baker [17].

The logic diagram of fusion development scenario with FIRE as the major burning plasma device is shown in Figure 6.3. The elements of this development path are described below.

Burning plasma physics and configuration optimization

The major next step plasma physics facilities in the International Portfolio Approach are:

1) **Advanced tokamak physics facilities** to address the high-β, high-bootstrap and non-burning plasma physics issues needed to support the ARIES physics design goals. This would require strongly shaped plasmas, with flexible plasma control capability to explore the full range of advanced tokamak capabilities. The goal of these major next step experiments would be to extend the range of advanced tokamak experiments toward power plant plasma parameters, especially ρ^*. A major objective of these experiments would be to achieve and study advanced plasma regimes in non-burning plasmas with β_N = 5 and bootstrap current fractions = 90% that are sustained for near steady-state

conditions (many plasma current redistribution times). The programs planned for KSTAR, now under construction in South Korea with a construction cost of ~ $300M, and JT-60SC under design in Japan with an estimated cost of ~ $500M would be sufficient to address these issues in a non-burning plasma at parameters approaching those needed for ARIES. The larger of these facilities would have advanced tokamak performance capability sufficient to achieve equivalent $Q_{DT} \sim 1 – 2$ while operating in deuterium. Very limited DT experiments might also be carried out. These facilities would also address the integration of the advanced plasma confinement with high power plasma exhaust technology, and the integration of superconducting coil technology with the tokamak environment.

2) **Burning plasma facility(s)** to address the burning plasma physics issues expected in ARIES-like plasmas. These include to study and determine: conditions needed to achieve burning plasma conditions, control of an alpha heating dominated ($P_\alpha/P_{ext} \sim 2$) plasma, the operating window for stable operation with respect to fast alpha driven instabilities, and study and control plasma heat and particle (alpha ash) exhaust. A plasma facility such as FIRE with pulse lengths ~ 2 plasma current redistribution times would be sufficient to address burning plasma issues in the Elmy H-Mode regime ($P_\alpha/P_{ext} \sim 2$). Since this regime does not extrapolate to an economic power plant, it is necessary to extend the burning plasma experiments into the advanced tokamak regime with physics parameters approaching ARIES. The most expeditious way to do this is to incorporate the results from the advanced tokamak facilities into the later phases of the burning plasma experiment. The FIRE experiment, being designed in the US with a construction cost of ~ $1.2B, has adopted strong plasma shaping, geometry and other advanced features identified by ARIES. FIRE has the capability to study ARIES-like advanced modes up to $\beta_N \sim 3.7$, $f_{bs} \sim 70\%$ and $P_\alpha/P_{ext} = 1$ under quasi-stationary conditions (=1 plasma current redistribution time).

3) **Fusion Plasma Simulator** to contain comprehensive coupled self-consistent models of all important plasma phenomena that would be used to guide experiments and be updated with ongoing experimental results. Most importantly, the Fusion Plasma Simulator would serve as the intellectual integrator of physics phenomena in advanced tokamak configurations, advanced stellarators and tokamak burning plasma experiments. It would integrate the underlying fusion plasma science with the Innovative Confinement Concepts thereby accelerating their development. This envisioned as a major long term effort requiring additional resources of about $0.4B over a $15 year period.

4) **Non-tokamak facilities** to extend physics understanding, and to develop and test the innovations to improve the toroidal magnetic configuration are an essential part of the magnetic fusion program. Diversified facilities at various stages of scientific exploration are needed to carry the fusion program forward. Two large stellarators (LHD, W-7X) and possibly a large compact stellarator will be available to test confinement, and beta limits under steady-state. The plasma simulation initiative, described previously to integrate advanced confinement and burning plasma physics, must also encompass the non-tokamak configurations. This is needed to facilitate the transfer of innovations from these non-tokamak configurations to the tokamak burning plasma experiments, and to then transfer

the scientific knowledge gained from tokamak advanced burning plasma experiments back to non-tokamak configurations.

5) **A strong base program** in plasma science and technology is needed to provide the scientific basis for the facilities described above, and to provide the technical infrastructure to exploit the capabilities of the next step facilities. In particular, strong computer simulation initiatives are needed provide the medium for integrating advanced confinement physics, burning plasma physics and plasma boundary physics, and for extending the results from the high intensity neutron source to improved designer materials and components.

Plasma Support Technologies

A strong base program in plasma support technologies (fueling, magnets, heating, PFC) including experiments on test stands is necessary to develop advanced technologies necessary for power plants. Experience on present and future high performance and steady state device as well as FIRE will provide a wealth data on individual technologies. Complete integration with burning plasmas is deferred to the follow-up step.

Low-Activation Material and Fusion Power Technologies

As described above, a strong base program, an intense neutron source facility and a CTF/VNS is necessary before proceeding with the DEMO.

Decision Point

Integration of Program Elements is needed to provide the technical basis for the decision on an Advanced Engineering Test Reactor (ETR). FIRE in combination with non-burning KSTAR and JT-60 SC and a strong burning plasma simulation program (Fusion Plasma Simulator) would provide the integrated physics basis (advanced confinement, high power plasma exhaust and burning plasma) needed for the Decision on proceeding with a tokamak-based Advanced ETR (Fig. 6.3). The integration of technology from the CTF/VNS with the super conducting long-pulse advanced tokamak and the advanced burning plasma tokamak would provide the technology basis for the decision on a tokamak Advanced ETR

The physics basis for a stellarator-based Advanced ETR would be provided by information from steady-state non-burning experiments like LHD and upgrades, W-7X and possibly a performance extension compact stellarator (CS), integrated with the burning plasma results from FIRE using the Fusion Plasma Simulator. The technology basis for a stellarator-based Advanced ETR would result from superconducting and plasma technologies developed on LHD, W-7X, KSTAR and JT-60 SC, and nuclear technologies developed on the CTF/VNS.

The output of this program would provide, in about two decades, the information needed to make a decision on proceeding to the Advanced ETR stage where the plasma physics and technologies needed for an attractive magnetic fusion power plant are integrated in a single power-plant-scale facility. The Advanced ETR would incorporate the advanced physics and technology characteristics that were developed and tested during the prior multi-machine period. During the initial operating phase of the advanced ETR the integration of the physics and technologies would be validated, and the facility would evolve into the DEMO.

The benefits of this type of diversified portfolio or multi-machine strategy have been described previously by Rebut (1991) [14], PCAST (1995)[15], Meade (2000)[16] and Baker (2000) [17]. The Diversified International Portfolio Pathway (Fig. 6.3) seeks to address the physics and technology issues and develop the required innovations at the earliest time and the smallest scale (lowest cost). The overall international program would be carried out on several complementary facilities distributed among the major parties, each facility would be optimized to address critical fusion science and technology issues in an integrated international program. This approach allows the individual steps to be undertaken more rapidly, and allows for a more streamlined management approach. The diversified portfolio approach also reduces the technical risk associated with single point technical failures, and failures of a technical approach. There is also flexibility to incorporate non-tokamak configurations in the overall program.

The capital cost of the major facilities in the next phase of the FIRE Based International Portfolio Development Plan are ~$3B (without CTF/VNS) and $5B with CTF/VNS as shown in Table 6.2.

Table 6.2.
Elements for the Next Phase of FIRE-Based International Portfolio

Base Physics and technology program			
Ongoing Advanced Tokamak program (DIII-D, C-Mod, AUG, JET,…)			
New Initiatives and Facilities		<u>Capital Cost</u>	
KSTAR	$0.3B		
JT-60 SC		$0.5B	
FIRE		$1.2B	
Fusion Plasma Simulator – Comprehensive/integrated simulation of BP/AT including non-tokamak configurations		$0.4B	
Fusion Materials Test Facility(s)			
Intense Neutron Source		$0.8B	
Component Test Facility			$2B
PFC test Facility		$0.05B	
Advanced Magnet Development facility		$0.05B	
Others			
Total		$3B	$5B

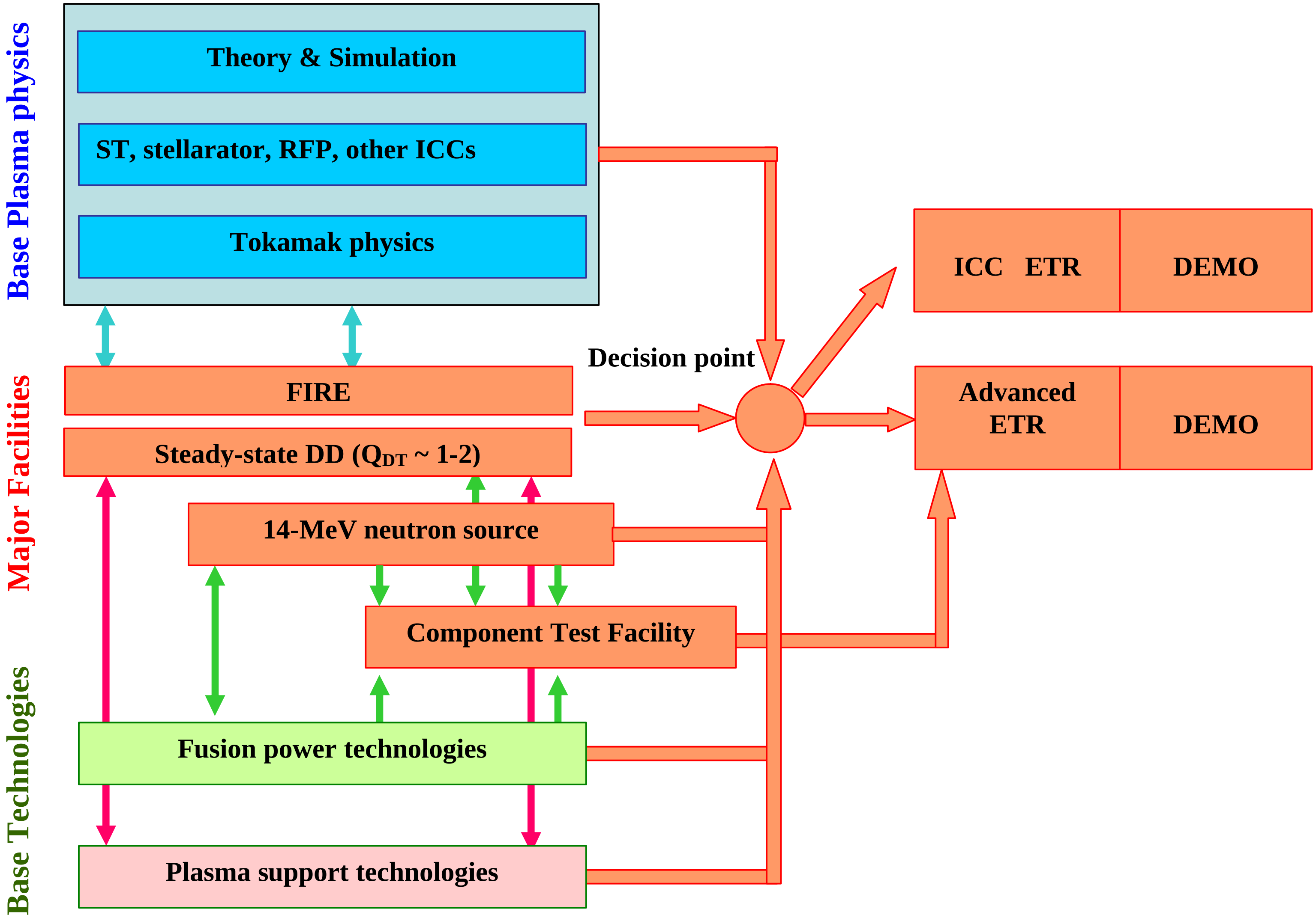

Fig. 6.3. Schematic of development path based on FIRE-class burning plasma experiment.

Issues and Responses

Several issues with regard to proceeding with FIRE-based development path scenario were identified and discussed during the Fusion Summer Study. These issues and responses are given below:

1) A follow-up integration step is necessary, may lead to a longer development path.

> It may be possible to combine Advanced ETR and DEMO functions in one device thereby requiring only one power-plant scale device to be built, which may shorten the path to an attractive fusion power plant.

2) Thorough examination of integrated burning plasma physics in advanced modes is limited by low number of full-power DT shots. Requires a follow-up physics & technology integration step.

> The number of shots is comparable to the number of full-power shots on present devices. A sufficient study of integrated burning plasma physics in advanced modes could be carried out through an integrated program plan that utilized the results from FIRE, the non-burning advanced tokamaks coupled with a strong fusion plasma simulation program.

3) FIRE-based scenario is not a lower cost option as the cost of follow-up integration step should be included.

> This scenario has a lower cost first stage which allows further optimization before the integration step, allowing either a more advanced and/or less costly integration step to follow. Most importantly, this plan requires the construction of only one power-plant-scale device.

4) It is an international portfolio approach requiring international participation. However, the international community is planning to proceed with ITER.

> Many of the elements of this international portfolio are already in place or under consideration. Since the construction of ITER is not certain, the design study and optimization of the FIRE device should continue in case ITER is not constructed. In addition, FIRE device itself is a strong candidate as a national base program device in support of ITER-based scenario.

6.3. Fusion development scenario based on IGNITOR-class burning plasma experiment

The major advantage of IGNITOR is demonstration of fusion burn, a major milestone for fusion energy development, at earliest date and at the lowest cost. Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes.

As an element of a national base program, IGNITOR would support ITER-based or FIRE-based development scenarios.

6.4. Role of ICC's in the Fusion Energy Development Plan

A sound magnetic fusion energy development plan includes the advancement of a portfolio of magnetic confinement configurations as one of its key elements. This is necessary for generating a validated and reliable predictive capability for magnetic confinement that spans multiple concepts and for ensuring that decisions on future steps will be the best from a range of choices. The portfolio includes a spectrum of toroidal configurations, including the tokamak as well as non-tokamak variants, which are distinguished by variables such as the plasma shape, the magnetic field twist, the degree to which their magnetic fields are generated by plasma currents or by coils, and how they are maintained in steady-state. The portfolio also includes concepts quite different from the tokamak which strive to make the path to fusion energy much faster and/or cheaper. All can contribute to decisions on fusion development beyond the burning plasma experiment and to the overarching goal of developing a predictive capability for designing fusion energy systems.

In the U.S. program, all non-tokamak configurations are often called Innovative Confinement Concepts (ICCs). The pulsed tokamak is sufficiently developed to be the basis for a burning plasma experiment (BPX) which will be used to develop the physics and technology of burning plasmas for magnetic fusion. The broader portfolio is being developed with a view to developing the best fusion energy sources and for advancing the fundamental understanding of plasma physics that comprises the scientific basis for fusion energy. The requirement for coherent integration across elements in the fusion program drives each element to develop a level of understanding and predictive capability such that knowledge transfer across magnetic configurations becomes possible. In this sense, developing a predictive capability for ultimately designing the best fusion power plant is the integrating principle across program elements.

In the U.S., a framework for studying ICCs has been established in recent years, with options advancing through stages of development. Ideas are initially explored at the Concept Exploration (CE) level, progress to more integrated configuration studies at the Proof-of-Principle (PoP) level, and approach fusion parameters at the Performance Extension (PE) stage. The U.S. has proof-of-principle programs in spherical tori, compact stellarators, and reversed-field pinches. Spheromaks and field-reversed configurations are at the concept exploration stage. In the worldwide program, the tokamak and the stellarator are currently at the Performance Extension stage.

The development of ICC's in the framework of a fusion energy development plan leading to DEMO is shown in Fig. 6.4. It is expected that the portfolio will mature, with concepts advancing from PoP to PE, and from CE to PoP, based on merit, in parallel with the construction and operation of a burning plasma experiment. The role of this advancing portfolio in the overall development path is explained next.

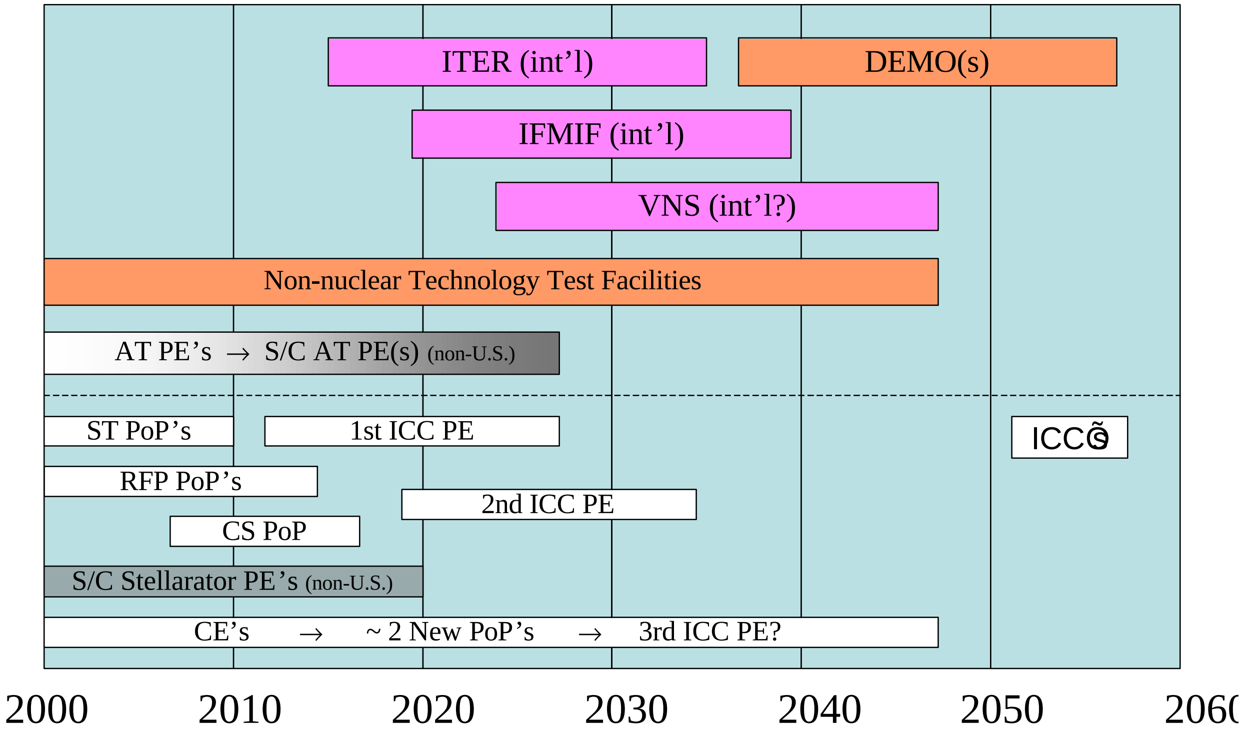

Fig. 6.4. Development Plan Leading to an MFE DEMO.

6.4.1. Role of ICC's in DEMO Development

The knowledge base for DEMO configurations decisions will require a mature portfolio. This requirement can be satisfied by continuing to follow the current ICC development strategy. The three configurations that are now at the proof-of-principle stage are more closely related to the tokamak and in the next 5-15 years are natural candidates for promotion to performance extension, joining tokamak and the stellarator at the PE stage. (Fig. 1 assumes, for planning purposes, that two of the three are promoted.) Concepts presently at the CE stage could advance to the PE stage on a somewhat longer time scale. Clearly a substantial performance extension knowledge base spanning a large range of toroidal configuration variables can be made available by the time DEMO decisions need to be made, in about 2025.

This plan has an excellent chance of developing magnetic configurations by ~2025 that are preferable in terms of power plant economics to the tokamak configuration being adopted now as the basis for the BPX. It would be desirable for the DEMO design to adopt such an improved configuration, but a question is whether it would require an intervening burning plasma step to confirm the new configuration, delaying fusion development. While the possibility of such a delay cannot be ruled out entirely at this time, it can plausibly be avoided. Consider for purposes of illustration the stellarator, which already has two PE-class experiments (LHD in Japan and W7-X in Germany) and could add a third in the late 2010's if the CS is successful at the PoP stage. There will be a substantial experimental data base on stellarator physics and long-pulse integration at near-power-plant plasma parameters by 2025. Meanwhile, the BPX will develop a knowledge base on toroidal physics in the regime of alpha-dominated, large-size plasmas in a tokamak. Together, this base of knowledge will underlie validated predictive models for advanced toroidal systems performance. Given the programmatic commitment to dramatic advances in fundamental understanding and predictive theory and modeling of both tokamak and stellarator physics in this time period it is probable that sufficient fidelity in our predictive capabilities will allow for the performance data of a tokamak BPX to be extrapolated to the stellarator with sufficient confidence for a DEMO step. On the technology side, the knowledge developed in BPX should be readily transferable to stellarators.

The illustration above depends on the close similarity of the stellarator to the tokamak. More importantly, to firmly establish a basis for any DEMO, it will be crucial to demonstrate more general predictive capability in toroidal magnetic confinement physics, spanning the full range of configuration variables. The robustness of predictive science will be demonstrated only when major configuration knobs are adjusted and the outcome correctly predicted. The elements of the toroidal magnetic portfolio must therefore mature together and in synch with the tokamak BPX.

While it must be acknowledged that the path to fusion beyond the BPX could prove to be more complicated and longer, success in developing the ICC's does not inevitably mean a delay in developing fusion energy. Indeed, the strategy of developing a portfolio of configurations and predictive capability in parallel with a tokamak BPX increases the range of options available for choosing the best path beyond the BPX to a to a practical fusion DEMO and may well shorten the development time.

6.4.2. Role of ICC's in Component Test Facility Development

The discussions at Snowmass-2002 have highlighted the importance of a volume neutron source, or component test facility, as an element of the fusion development plan leading to DEMO. Its role in this plan is to support the development of fusion power plant components such as blankets by providing a facility for testing them at moderate to high neutron flux and fluence and under power plant conditions. With sufficient progress in their physics development, an advanced tokamak or a spherical torus operating at substantial duty factor (~30%) but possibly low fusion gain (Q=1-2) could meet the requirements for component testing. The challenge is to demonstrate adequate physics performance and develop a non-inductive operating scenario on the needed timescale, i.e. almost two decades before DEMO operation. The ST is of particular interest for this application because of its compact size. If its primary PoP physics goals (high beta, good confinement, and non-inductive current drive development) can be expeditiously achieved, the ST could become the first of the current PoP concepts to move to a PE-class device, which could complete the ST physics development needed for a component test facility. An updated study of component test facility options would take into account advances in understanding and performance of the concept portfolio.

6.4.3. Implications for Achieving Predictive Capability in Toroidal Confinement

A key element of our strategy for fusion energy research is a permanent commitment to deepening our understanding of the physics of magnetically confined plasmas and developing a reliable, validated predictive capability for their behavior. Such a capability is needed for designing facilities and the experiments conducted on them to have a high probability of success.

The ICC portfolio has a central role in this strategy because they provide strong tests of theoretical ideas and they produce experimental data needed to validate models applicable across the portfolio. A flexible, well-diagnosed tokamak burning plasma experiment is a key requirement of this strategy, so that it can contribute to fundamental physics understanding needed to predict performance not only in tokamaks but in other closely-related configurations as well.

In summary, advancement of a portfolio of magnetic configurations is a central feature of our plan for fusion energy development. The portfolio will provide the knowledge base for selecting a DEMO configuration, will support the design of a component test facility, and will rapidly advance the predictive capability for fusion plasma behavior. The portfolio must be developed in a coherently integrated program, not as separate concepts, to test physics understanding and provide efficient knowledge transfer across the portfolio. The integrated development of a BPX, a portfolio of configurations, and theory and modeling will provide the predictive capability needed to develop fusion energy.

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