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Prospects and issues for commercial fusion power systems

Robert W. Conn [a],*, Farrokh Najmabadi [b], Mark S. Tillack [a]

[a] *Fusion Energy Research Program, Division of Mechanical Engineering, Department of Applied Mechanics and Engineering Science, University of California, San Diego, La Jolla, CA 92093-0417, USA*

[b] *Fusion Energy Research Program, Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093-0417, USA*

Abstract

As one alternative source of energy for the future, fusion power will be required to demonstrate that it can be a safe, clean and economically attractive option in an increasingly diverse and competitive energy marketplace. Top-level requirements have been developed and used to guide the development of fusion power concepts, most recently, the ARIES-RS conceptual power plant design based upon the tokamak operating in the reversed shear MHD mode. This design is shown to have the potential to meet the necessary requirements. We review the present status of this and other power plant designs, identify the key fusion R and D issues in a variety of technological areas, and point to the need for a coordinated, and international, R and D effort to achieve the ultimate goal of a commercially desirable fusion system. © 1998 Elsevier Science S.A. All rights reserved.

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1. Introduction

Progress during the past 20 years of research on fusion energy has made it possible for the first time to produce significant amounts of energy from controlled fusion reactions of deuterium and tritium (DT) in the laboratory. With growing confidence in our ability to produce burning plasmas with significant energy gain, attention inevitably turns to ways of utilizing these new capabilities in a practical system for the benefit of mankind.

One of the enduring visions for fusion research is to provide a clean and essentially limitless supply of energy. As one of many alternative energy sources, fusion should and will be subjected to a rigorous set of requirements based on its safety and environmental features as well as its economic attractiveness in an increasingly competitive and diverse energy marketplace. Based on a series of conceptual fusion power plant design studies begun in the 1970s for both magnetic and inertial confinement approaches to fusion, it is possible to begin to translate commercial requirements into the design features that must be met if fusion is to play a role in the world's future energy mix.

In this paper, we present and assess the status of power plant design studies and evaluate the prospects that continued progress in international fusion research and development (R and D) will lead to a commercially desirable end-product. The technologies associated with the power core are far less advanced than enabling technologies for

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* Corresponding author.

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fusion plasma experiments, since the latter have evolved in conjunction with large fusion experiments. And yet the attributes which permit an attractive power plant are dominated by the design, material choices and performance of plasma-facing and nuclear components. Needed R and D will be assessed in the context of the existing programs in the US and around the world today.

2. Utility perspective and power plant goals and requirements

As one of the alternative sources of energy, fusion should and will be required to demonstrate that it can provide a safe, clean and economically attractive option in an increasingly competitive and diverse energy marketplace. Based on interaction and advice from electric utilities and industry, a set of criteria for fusion power is derived Refs. [1,2]. A similar set of criteria has been developed by the EPRI fusion working group [3]. These criteria were translated into a set of quantitative top-level requirements which are presented in Table 1.

Requirements 1–4 (Table 1) are included to circumvent the difficulties experienced by fission and, to some degree, will be faced by fossil fuels in the future. Fusion should be easy to license by the national and local regulating agencies, and be able to gain public acceptance. Realization of the full safety and environmental potential of fusion will help fusion to achieve a cost advantage over other sources of electricity. Fusion power plants can be designed to achieve these criteria only through the use of low-activation material and care in design. The fact that fusion has no atmospheric impact is also a powerful and positive attribute.

Table 1
Commercial power plant top-level requirements

1. No public evacuation plan required: total dose <1 rem at site boundary
2. Generate no radioactive waste greater than Class C
3. Must not disturb public's day-to-day activities
4. Must not expose workers to a higher risk than other power plants
5. Closed tritium fuel cycle
6. Must provide for operation at partial load conditions (50%)
7. Maintainability of power core
8. Must operate routinely with less than 0.1 unscheduled shut-down per year, including disruptions
9. Cost of electricity must be competitive (in 1995 mill kWh^{-1}):
   Goal = 65 mill kWh^{-1}
   Requirement = 80 mill kWh^{-1}

Requirements 5 and 6 (Table 1) are easy to achieve but represent powerful arguments for an energy source. Because there is no need to ship radioactive fuel and/or massive amount of fossil fuel to the site, fusion has a great advantage that circumvents strikes, natural calamities, and adverse supplier actions. This helps the utility better control their self destiny. Fuel availability is high in that all elements in the fuel cycle are in abundant supply with no critical resource shortages. There seems to be no difficulty in designing a fusion plant to operate at partial power.

Requirements 7 and 8 (Table 1) are essential for the success of any commercial product. Today's experiments are, by their charter, not intended to provide detailed engineering data to support the design, construction, and operation of a power plant. Conceptual design studies can show schemes for rapid maintenance of the fusion core (mean time to repair) but reliability data for various components are essential to estimate and improve mean time between failures. These requirements should be addressed in the development path of fusion power and are perceived as the most difficult to achieve in a limited time program.

As fusion is a new technology in the energy marketplace, it must have a cost advantage to offset the inherent technical risk or it will never be widely endorsed. The cost here reflects a complete life-cycle costs, that is, it includes cost associated with other elements of the case (e.g. costs due to delays in licensing and/or public opposition to evacuation plan, costs due to decommissioning and waste disposal, carbon taxes, etc.). Top-level requirements and goals for cost of electricity (COE) were adopted for the Starlite project based on estimated costs of competitive sources of electricity at the time of introduction of fusion in the market place [2,4]. These requirements and goals for COE also are in line with projections of future power plant costs based on energy forecasting models [5]. While these cost requirements represent a reasonable starting point, further effort in reducing the cost is essential to ensure successful introduction of fusion.

A demonstration power plant will be built and operated in order to assure the user community (general public, utilities, industry) that fusion is ready to enter the commercial arena. Accordingly, the Fusion Demo should clearly demonstrate that goals and requirements for a commercial fusion power plant can be achieved. The Demo need not meet 100% of all commercial power plant requirements and goals, but the risk in eventually meeting those goals should be acceptable. In particular, Demo should use the same technologies as planned for commercial power plants since introducing a new technology (e.g. different plasma operating regime, coolant, or structural material) would require that a new development path be initiated. A detailed mission statement for the Fusion Demo has been compiled for the Starlite project and given in Refs. [1,2]. The major differences between requirements and goals for Demo and commercial plants is limited to three categories: size, cost, and reliability/availability. In principle, smaller and hence, a lower capital cost, Demo is preferred. However, the Demo should be of sufficient size so that it can scaled with confidence to a commercial power plant. In addition, the Demo COE, which is a function of its size, should be within an acceptable range. The higher cost of electricity from Demo reflects first-of-a-kind costing as well as experience with Demo systems which usually results in a lower cost for later models (i.e. commercial plants). One of the main outcomes of Demo operation is the experience gained in operating an electricity-producing fusion plant. As a result, it is expected that Demo operation will lead to improved reliability and availability. The top-level requirements for the Demo and commercial fusion plants have been discussed in detail in Refs. [1,2].

3. Review of fusion power plant studies

There has been tremendous progress in our views of future fusion power plants. Twenty years ago, fusion power plants were envisioned as large, pulsed systems based on conventional steel technology with complex geometries extrapolated from then-existing experimental devices. More recently, the desire for a more commercially attractive product has motivated intense research resulting in smaller machines through improved plasma performance, steady-state operation, and better understanding of high-performance, low-activation material.

3.1. Magnetic fusion

3.1.1. Magnetic confinement concepts

In recent years, tokamaks have enjoyed the focus of the worldwide fusion energy programs, having logged the most impressive confinement performance results. In the late 1980s, operation at high bootstrap current fraction, within a self-consistent plasma MHD equilibrium and stability framework, as the approach to steady-state operation was first proposed in the ARIES [6] and SSTR [7] 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 ($A = 4.5$) and low plasma current ($I = 10$ MA) at a relatively high poloidal-β. Detailed MHD and current drive analyses [6,7] have showed that the maximum bootstrap fraction in this class is about 70% with most of the driven current located near the magnetic axis, leading to current-drive powers of about 100 MW delivered to the plasma.

The trade-off between MHD and current-drive identified by the ARIES and SSTR studies has resulted in research in new advanced tokamak modes during the last ten years. Furthermore improvements in plasma performance has been found through elevated central safety factor [8], reversed magnetic shear [9], or at very low aspect ratios [10]. All these equilibria have a high bootstrap current fraction which allow steady-state

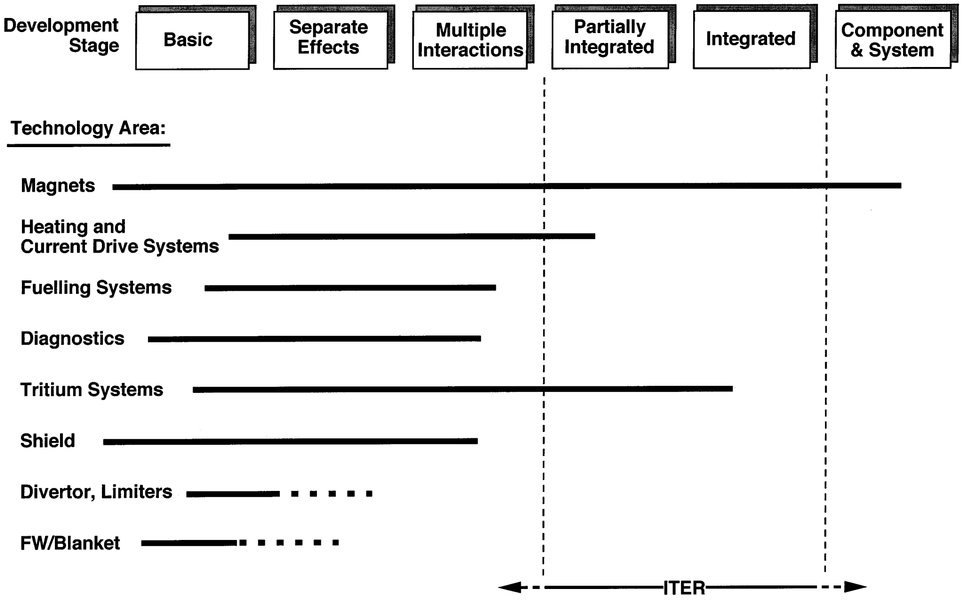

Fig. 1. The relative level of development of fusion technologies.

operation. Intensive experimental activity is ongoing in large tokamaks on reversed-shear plasma mode and resent results on the performance on low-aspect-ratio (spherical) tokamaks are encouraging.

The dominance of tokamaks has not always been the case, and recent developments in the US and around the world have elevated alternative magnetic confinement concepts to a new level of attention. At present, the five most-developed concepts in addition to the standard tokamak include spherical tokamaks, stellarators, reversed-field-pinches, field-reversed configurations, and spheromaks. A much larger list of options exists, but their database is less than those above.

One important reason for studying a range of confinement concepts is that the study of more than one plasma confinement system configuration advances plasma science and fusion technology in ways not possible in one system only. Examples of past discoveries and innovations in alternative concepts of significance to tokamaks and fusion plasma physics in general are numerous. They include the discovery of bootstrap current, invention of helicity-injection current drive, development of neutral beam heating, discovery of the dynamo effect in the laboratory, to name just a few. In fact, a fusion power plant will likely draw on the broad-based fusion science foundation that comes from experimental and theoretical studies in a variety of plasma confinement approaches including ‘alternative concepts’.

3.1.2. Magnetic fusion energy technology development

During the past 20 years, numerous design concepts for power core components have been proposed, and R and D programs for a number of these have been implemented in varying degrees throughout the world [11]. Different technologies are at very different stages of development, with the so-called ‘enabling technologies’ enjoying a much greater level of progress due to their coupling to current and planned plasma confinement experiments. Fig. 1 represents pictorially this disparity in the level of development of ‘power core’ technologies as compared with enabling technologies.

With the emergence of ITER [12] as a centerpiece of international fusion energy research, and especially considering its mission to test power-plant-relevant technologies, the need for accelerated efforts to develop advanced in-vessel power plant components is becoming more urgent. ITER is having a significant impact on the development of nuclear technologies, but its mission and device parameters are far less demanding than those of a power plant and as such, many of its in-vessel technologies will require dramatic improvement and/or design innovation in order to provide a competitive end-product. From this point of view, we refer to ITER technologies as ‘conventional’, whereas technologies capable of delivering an attractive and competitive power plant as ‘advanced’.

The most appropriate criteria for choosing from among advanced technology options are the mission requirements as elaborated above. Safety and environmental attractiveness have been major drivers for the past decade, since they are viewed as important discriminators between fission and fusion. The possibility to provide a fusion energy system that can be designed without the need to consider the deep burial of waste or worst-case accidents that affect the public has been established in studies such as ARIES-RS [13] and SEAFP [14].

However, in a market economy such as that of the US, economic goals are as important as safety and environmental goals. No fusion plant ever would be built by a private company if significantly cheaper alternatives exist (considering all quantifiable economic factors—taxes, regulatory costs, fuel supply uncertainties, etc.—properly internalized). Predictions of the future COE and projections for the cost of power plants, which today are understood only through conceptual design studies, are both difficult to make and use to establish the economic competitiveness of fusion. Nevertheless, several key factors in the cost of electricity are known to be important, e.g. capital cost, availability, thermal conversion efficiency, and power density. Economic competitiveness demands agressively pursuing improvements in each of these attributes, as well as seeking innovative solutions which could dramatically affect one or more of them, because existing technologies appear to be far from satisfying the bottom-line COE required for fusion to be adopted within the foreseeable future.

During the past decade, advanced technology programs around the world have focused on a few ‘mainline’ options, with minimal resources devoted to highly innovative concepts. This strategy is consistent with a minimum-cost approach to technology development. As an example, the two principal choices for structural material are ferritic steels [15] and vanadium alloys [16]. Some fusion-specific work continues on SiC/SiC composites [17], but their development is far less advanced within the world’s various fusion programs.

New, reduced-activation variants of ferritic steel appear capable of meeting safety and waste disposal requirements, and are pursued in some parts of the world as the primary (if not the only) option for near-term R and D. However, fundamental limitations on thermal conductivity and high-temperature mechanical properties restrict the power density and thermal conversion efficiency to levels which place severe strain on the economic performance of the power plant.

Vanadium alloys have been pursued in the US as the primary advanced option in recent years, owing in part to their high thermal stress factors, their potential for high temperature operation and their potential for long service life. These features provide the hope that heat fluxes expected from advanced plasma confinement concepts could be removed without violating fundamental engineering limits. As compared with SiC composites and steels, vanadium alloys are not widely used in other industries, such that the database for such alloys is small and will require substantial effort funded by fusion programs. The cost of the raw material for vanadium alloys is now an order of magnitude greater than that for steels. Without sharp reductions, this fact alone will require the restricted use of vanadium alloys to specific subsystems in order to prevent a very high capital cost from offsetting its performance advantages.

Besides structural materials, blanket design options can be classified by coolant and breeder. To achieve high thermal conversion efficiency, high-temperature operation is a fundamental requirement. Helium and liquid metal coolants represent the best choices to achieve efficiencies in excess of 40%. The primary breeder options are lithium ceramics (such as Li_2TiO_3, Li_2ZrO_3 or Li_4SiO_4) or liquid metals. Here again, differences in strategy appear in different countries, with the US adopting a more aggressive approach by pursuing liquid metal breeder and coolant as a top candidate.

Plasma-facing surfaces offer unique materials and engineering design challenges, especially in regions where direct contact with plasma is possible, such as on limiters or divertor plates. The performance of materials facing the plasma can and does have a major impact on plasma performance, and such performance can be dramatically degraded due to limitations associated with component erosion, reliability and lifetime. Even if components can be designed to resist erosion, concentrated heat flux, and high neutron fluence, off-normal events such as electromagnetic transients, halo currents, runaway electron bursts, and disruptions are serious additional threats to their safe and reliable operation. As advanced tokamaks are currently envisioned, a large fraction of the total fusion power is deposited on plasma-interactive components such that high temperature operation may be necessary in order to maintain acceptable net thermal efficiency. No credible design solutions are known today which meet all of the requirements imposed for an attractive power plant, making plasma-interactive components a critical feasibility issue for fusion.

The combination of a harsh operating environment within a burning fusion core, together with challenging goals for safety, environment attributes and economics, points to the need for further innovations and advancement in our technological capabilities for fusion power systems. These will come about only by devoting significant additional resources to advanced technology research and development.

3.2. Inertial fusion

Progress in inertial confinement fusion (ICF) has been very rapid in the past few years [18]. Most of the activity has been centered on glass lasers. Of special importance are the development of new storage media and beam smoothing techniques (for direct drive). Both developments have made the glass laser a serious contender for inertial fusion energy (IFE) applications. This progress has also resulted in the initiation of the National Ignition Facility (NIF) with a 1.6 MJ laser to investigate ignition in ICF capsules. A similar facility is proposed for research in France. Significant progress has also been made in other ICF drivers such as KrF lasers and light-ion beams. Separate from defense applications, the bulk of the worldwide IFE research is focused on heaving-ion accelerators which promise a high driver efficiency.

Assuming that proposed ICF facilities will be successful and the target/driver physics is well understood, the next step in the IFE development path requires drivers with sufficient rep-rate (several Hz) and efficiency. Large-scale and economic production of IFE targets is also a major challenge.

Technology issues for inertial fusion power plants share some commonalities, and a number of key differences, with MFE. Aside from the obvious pulsed nature of IFE, major differences appear due to the absence of magnetic fields, less restrictive vacuum and impurity control requirements, and much different configurational constraints. Choices related to the fusion pellet or target (direct drive, indirect drive, fast-ignitor) and the driver (laser versus ion beams) also strongly impact the features and feasibility of in-vessel technologies. While differences in the design solutions and technology issues are driven by the particulars of the approach to confinement, the top-level requirements on safety, environment and economics are shared amongst all approaches to fusion.

Few resources have been devoted to power core technology R and D for IFE systems. The majority of the effort to date has focused on conceptual design studies and on the development of models for the response of the main target chamber. Design concepts often feature liquid or flowing particulate protective surfaces, such that structural material issues become less dominant than in MFE, while focus is more on the behavior of the wall protection materials in the chamber. As with MFE, numerous designs have been proposed and the issues have been examined and cataloged [19,20].

Some aspects of inertial fusion energy offer significant potential advantages in meeting requirements for an attractive fusion power plant. Decoupling of the driver, target and chamber allows design flexibility not present in conventional magnetic fusion power cores. For example, the ability to redirect the driver and target allows the possibility for highly enhanced availability, since a failed chamber could be taken off-line and repaired while the plant continues to operate with one or more ‘spare’ chambers. The ‘openness’ and decoupling of systems also greatly simplifies maintenance. The most sensitive and expensive elements can be far removed from the fusion core.

Smaller plant sizes are also possible with IFE. This attribute not only provides greater flexibility for the plant owner, but also could have a major impact on the ‘cost of entry’ for the technology as a whole. The large plasma size (and consequently high cost) required to create a break-even or ignited plasma in MFE is one of the most serious drawbacks of the MFE approach to date.

Public safety and waste concerns arise primarily due to large inventories of radioactive materials. As with MFE, activation of materials and inventory of tritium are highly design-dependent. In an IFE plant, tritium is contained in the breeding medium, the chamber gas exhaust, and the target factory. Activation of structures will exist even with thick liquid wall protection, and an additional, possibly large source of activation will occur from target debris (which accounts for several tonnes of irradiated material per year).

Economic assessments of IFE power plants (see, for example [20]) estimate a cost of electricity comparable to those emerging in MFE studies. The capital cost of the power core is significant, but not a dominating factor as compared with the driver, power conversion equipment, and so on. High recirculating power as a result of the relatively low efficiency of many driver candidates is a serious concern (possibly as high as several hundred MW), because it places even greater demands on the thermal conversion efficiency in order to achieve acceptable net plant efficiency.

4. ARIES-RS

The ARIES-RS design was guided by the top-level requirements discussed in Section 2 and Table 1 [13,21–24]. A high performance plasma core operating in the reversed-shear mode is chosen (see Fig. 2). Reversed-shear plasmas achieve high values of normalized β (5.5) and absolute value of beta and have a large bootstrap current fraction (90%) which is very well aligned with the required equilibrium current–density profile. It also appears that the transport is suppressed in this regime. The primary characteristics of this regime are a hollow current profile, a non-monotonic safety factor profile, and relatively peaked pressure profile. The current-drive analysis has showed that a three current drive system is necessary: ICRF fast waves for central regions, high-frequency fast-waves for mid-plasma, and lower-hybrid for edge-plasma. About 100 MW of current-drive power is necessary for operation at steady-state. It was found that operation with a radiative mantle would require both the edge density and plasma Z_{eff} to be too high resulting in very large current-drive powers. As a result, a radiative divertor has been used in which most of the power is radiated inside the divertor through injection of neon impurities.

Safety and environmental attractiveness are attained in large part from the choices of the basic materials. Lithium-cooled plasma-facing components provide adequate tritium production without the need to use beryllium as a neutron multiplier, and the volume of other materials exposed to neutron irradiation is minimized. Use of vanadium in the high-temperature zones provides sufficiently low levels of afterheat such that worst-case loss-of-coolant accidents can be shown to result in very low release of radionuclides (below 1 rem at the site boundary), fully acceptable from the viewpoint of standards and regulations. Complete elimination of water in the power core and the use of inert gas in the containment building are additional measures that reduce the potential for chemical reactions.

Most of the design effort was devoted to developing a credible configuration which could meet all of the economic goals [21]. The choice of

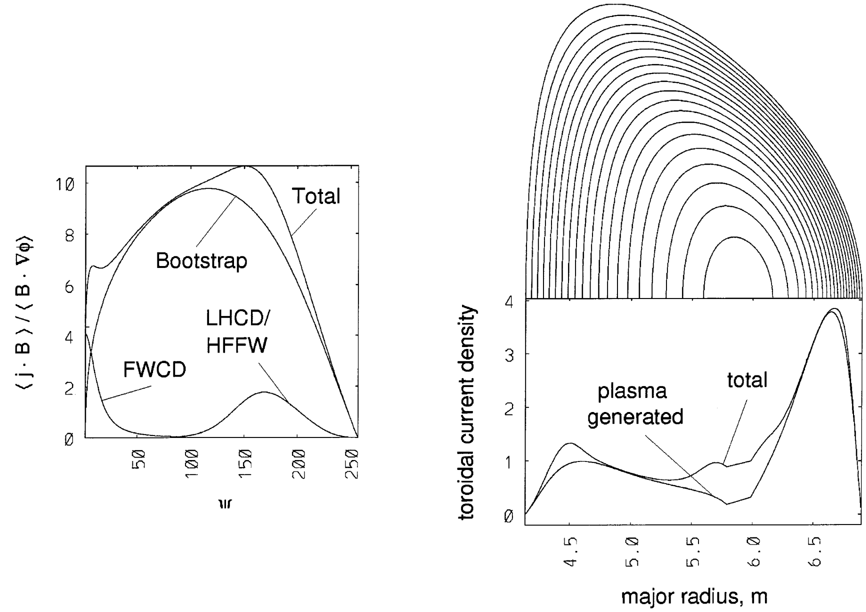

Fig. 2. ARIES-RS reference plasma equilibrium parallel current profile as a function of poloidal flux, the plasma flux surface contours, and toroidal current density as a function of the major radius.

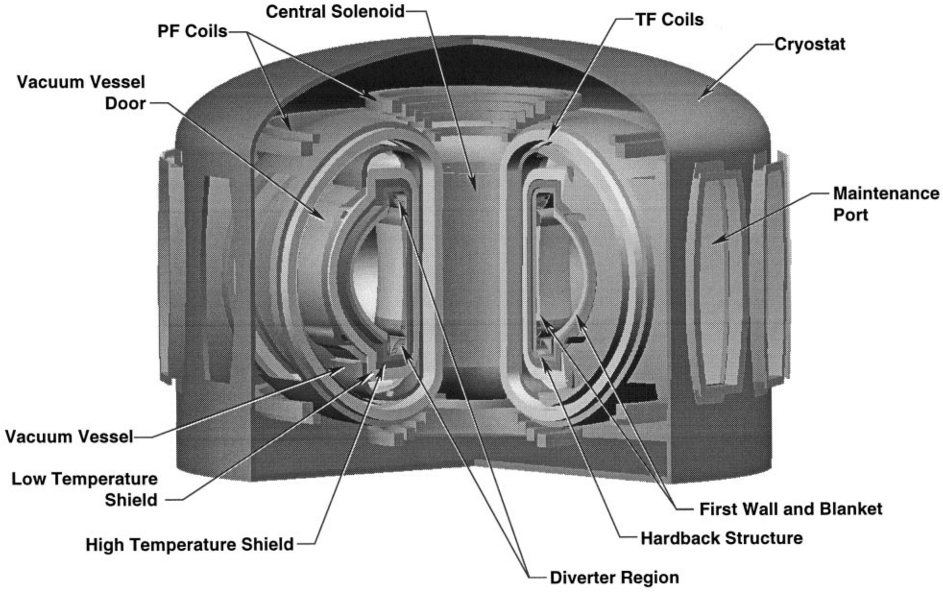

Fig. 3. Cutaway of the ARIES-RS power core.

lithium-cooled vanadium structures allows both high thermal conversion efficiency ($\eta = 46\%$ using 610°C coolant outlet temperature and a Rankine steam cycle) and high power density (ARIES-RS has a peak neutron wall loading of 5.6 MW m^{-2} at the midplane and a peak surface heat flux of 6 MW m^{-2} in the divertor). Rapid removal of full sectors is provided through large horizontal ports

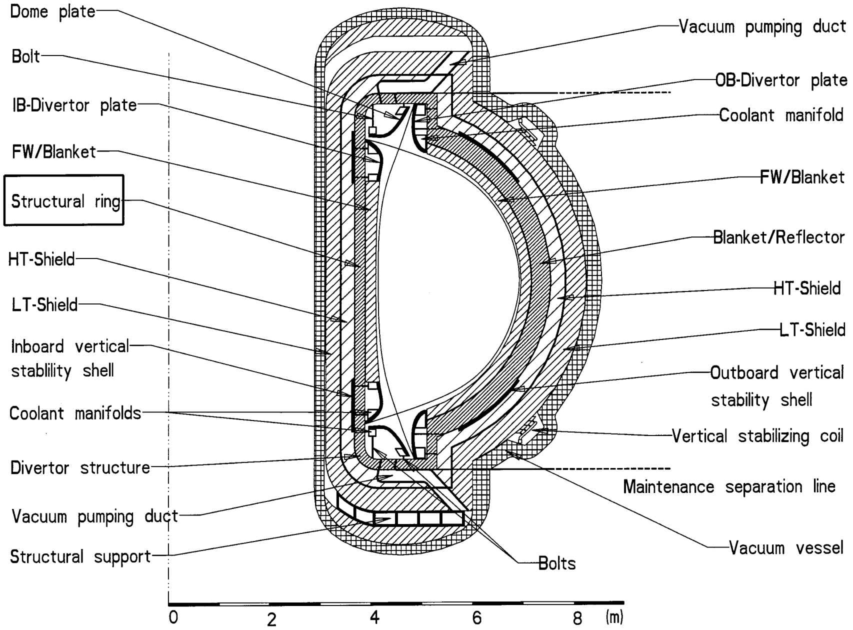

Fig. 4. Vertical cut through a sector.

(see Figs. 3 and 4), followed by disassembly in the hot cells during plant operation. The overall goal was a design allowing replacement of a sector in less than one month and parallel maintenance of all sectors during a shutdown. The simple blanket design with a small number of cooling channels and low mechanical stresses in the structure (given the successful development of electrically insulating coatings) provides a good basis for high reliability. In addition, vanadium alloys show the promise of an exceptionally long lifetime. Due to the low total volume of vanadium in the fusion power core, attained in part by restricting its use to the high-temperature zones, the high unit cost of the alloy is not expected to have a major impact on plant COE. An additional savings is made by radial segmentation of the blanket such that large segments can be reused.

5. Summary and conclusions

Progress in fusion research has been rapid over the past decade. Success with research in the large plasma experimental facilities has underlined the scientific feasibility of fusion while operation of ITER, which will produce a significant amount of fusion power, is already shifting the focus of fusion research towards demonstration of commercial fusion energy.

With this shift, the attractiveness of commercial fusion systems becomes more central. Fusion should and will be subjected to a rigorous set of requirements based on its safety and environmental features as well as its economic attractiveness in an increasingly competitive and diverse energy marketplace. While specific quantitative requirement may vary in different countries, the underlining theme of a safe, clean energy source with a competitive cost is a universal requirement for fusion. An attractive end-product requires development of necessary fusion technologies since the attributes of a power plant are dominated by the design and material choices, and by the performance of plasma-facing and nuclear components. Fig. 5 depicts the set of experiments and facilities that will be needed to address the full range of issues. Developing fusion power core and power plant technologies will require a substantial increase in efforts in a world where financial re-

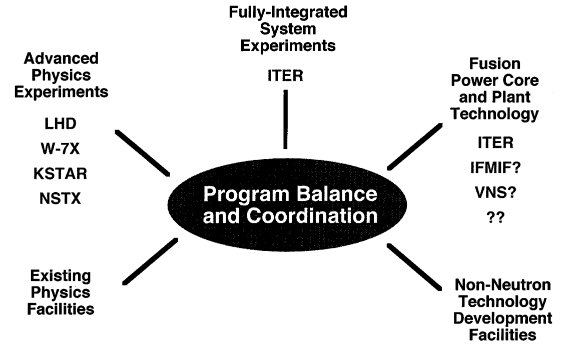

Fig. 5. Achieving an attractive fusion power plant requires coordinated efforts worldwide.

sources are constrained. In perhaps the most dramatic example, the budget for fusion research in the US has decreased by about 1/3 over the past 2 years, while the budgets for fusion in Japan and the European Union have been about constant. As research budgets become constrained, a more coordinated and intensive world-wide program in fusion technology aimed clearly at developing an attractive fusion power concept is an essential element for a successful fusion program. We believe this is the only viable path to success in the near future and thus urge partners throughout the world, perhaps using the framework already developed for the ITER program, to join together more strongly for the objective of developing a new energy source for the future.

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