

ASSESSMENT OF OPTIONS FOR ATTRACTIVE COMMERCIAL AND DEMONSTRATION TOKAMAK FUSION POWER PLANTS[†]

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ABSTRACT

The Starlite Project was initiated to investigate the mission, requirements and goals, features, and the R&D needs of the Fusion Demonstration Power Plant based on tokamak confinement concept. It is obvious that the Fusion Demo should demonstrate that a commercial fusion power plant would be accepted by utility and industry (*i.e.*, it is affordable and profitable) and by the general public and government (*i.e.*, it has superior safety and environmental features). Therefore, as the first step in the Starlite project, a set of quantifiable top-level requirements, and goals for both commercial fusion power plants and the Fusion Demo were developed. Next, several candidate options for physics operation regime as well engineering design of various components (*e.g.*, choice of structural material, coolant, breeder) have been developed and assessed. In each area, this assessment was aimed at investigating (1) the potential to satisfy the requirements and goals, and (2) the feasibility *e.g.*, *critical issues* and credibility (*e.g.*, degree extrapolation required from present data base). This assessment led to the choice of the reversed-shear as the tokamak plasma operation regime and a self-cooled lithium design with vanadium alloy for blanket and in-vessel structures for detailed design. This paper presents a summary of top-level requirements and goals for fusion power and overviews the results of our assessment of tokamak plasma physics and technology options and designs.

I. INTRODUCTION

The demand for substantial increases in electrical power requirements has been forecast for decades. Conservation and use of relatively inexpensive fuel have reduced the need

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to develop new electrical energy sources affording more time for the development of fusion. But environmental concerns have severely curtailed many of the previously viable electrical sources. Improved power plants using existing energy sources are meeting with increasingly difficult regulations to continually improve both the local and the global environments. Fusion offers the promise of an abundant energy source that is not tied to national resources and will have only a minimal impact on the environment.

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. It is, therefore, essential to state the goals for commercial fusion power. Based on interaction and advice from electric utilities and industry, a set of criteria for fusion power is derived (Table 1) and discussed in Ref. 1,2. A similar set of criteria has been developed by the EPRI fusion working group³.

Table 1:

ELEMENTS OF THE CASE FOR AN ATTRACTIVE FUSION ELECTRIC POWER SOURCE

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1. Cost advantage over other available options.
 2. Eased licensing process.
 3. No need for evacuation plant.
 4. Produce no high-level waste.
 5. Reliable, available, and stable .
 6. No local or global atmospheric impact.
 7. Fuel cycle is closed and on-site.
 8. Fuel availability is high.
 9. Plant is capable of operation at partial load.
 10. Plant is available in a range of unit sizes.
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Table 2.
TOP-LEVEL REQUIREMENTS AND GOALS
FOR COMMERCIAL AND DEMONSTRATION FUSION POWER PLANTS

Element	Demo Plant	Commercial Plant
Must use technologies to be employed in commercial power plant	Yes	Yes
Net electric output must be greater than	75% commercial	N/A
Cost of electricity (COE) must be competitive (in 1995 mill/kWh)	80 (Goal) 90 (Reqmt)	65 (Goal) 80 (Reqmt)
No evacuation plan required for any credible accident: Dose at site boundary	< 1 rem total	< 1 rem total
Generate no rad-waste greater than	Class C	Class C
Must demonstrate public day-to-day activity is not disturbed	Yes	Yes
Must not expose workers to a higher risk than other power plants	Yes	Yes
Must demonstrate robotic maintenance of power core	Yes	Yes
Must demonstrate routine operation with less than (x) unscheduled shutdowns per year including disruptions	1	1/10
Demonstrate a closed tritium fuel cycle	Yes	Yes
Must demonstrate operation at partial load conditions at	50%	50%

Because fusion is a new technology in the energy marketplace, it must have a cost advantage (criterion 1) to offset the inherent technical risk of a new it will never be widely endorsed. The cost here reflects a complete life-cycle cost, 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.*). Criteria 2 through 4 in 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.

It should be demonstrated that Demo and commercial power plants can achieve the necessary degree of reliability (criterion 5). This criterion, to a large degree, should be addressed in the development path of fusion power. Today's experiments are, by their charter, and are not intended to provide detailed engineering data to support the design, construction, and operation of a power plant. This set of requirements is perceived as the most difficult to achieve in a limited time program.

The remaining criteria are foreseen as reasonably easy for fusion to achieve but are significant attributes for an electrical power source. No atmospheric impact is a powerful requirement. Fusion power plants can be designed such

that containment buildings or special safety systems will not be needed. Because there is no need to ship radioactive fuel and/or massive amount of fossil fuel to the site, fusion has a powerful 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. The last two criteria deal with how well the fusion plant will function in conjunction with the network and the energy demand. There seems to be no difficulty in designing a fusion plant to operate at partial power. Availability in a range of sizes is limited only by the fact that smaller sizes would tend to be more costly on a COE basis. If there were reasonable assurances that this set of high level criteria could be met by a demonstration power plant, then the decision to purchase a commercial fusion electrical power plant would likely be positive. Thus the intent for the Demo power plant is to use these criteria as guiding features to help structure its mission and goals, as has been derived and given in Table 2.

Top-level requirements and goals for cost of electricity (COE) were adopted for the Starlite project based on estimated cost of competitive source of electricity at the time of introduction of fusion in the market place⁴. These requirements and goals for COE also are in line with projections of future power plant costs based on energy forecasting models⁵. Several top-level requirements are related to criteria 2 through 4 and aim at achieving safety and environmental features of fusion. These result in stringent constraints on the sub-system choices and design.

The prior section discussed the goals needed for the commercial plant to be accepted and succeed. On the other hand, the Demo must “demonstrate” those attributes that would convince the utility or their investors and the public that this new technology, for long periods of time, is safe, economical, and does not harm the environment. 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 Ref. 1, 2. The corresponding set of top-level requirements for the Fusion Demo is listed in Table 2. The most important requirement is that the Fusion Demo should use the same technologies as planned for the commercial power plants. Introducing a new technology (*e.g.*, different plasma operating regime, coolant, or structural material) would require that a new development path be initiated. The only other 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 the first-of-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 Ref. 1, 2.

In the next sections, several candidate options for physics operation regime as well engineering design of various components (*e.g.*, choice of structural material, coolant, breeder) have been developed and assessed. In each area, this assessment was aimed at investigating (1) the potential to satisfy the requirements and goals, and (2) the feasibility *e.g.*, *critical issues* and credibility (*e.g.*, degree extrapolation required from present data base). This assessment led the choice of the reversed-shear as the tokamak plasma operation regime and a self-cooled lithium design with vanadium alloy blanket and in-vessel structures for detailed design. Detailed results of this assessment can be found in Ref. [2] and in these proceedings (Refs. 6–13).

II. PHYSICS REGIMES OF OPERATION

During the past several years, the ARIES/Starlite Team has investigated the feasibility and potential features of tokamak fusion power plants. The research also has aimed at identifying both the trade-offs that lead to the optimal regime of operation for a tokamak power plant and the critical plasma physics and technology issues. During the initial phase of the Starlite study, an assessment of various tokamak plasma operation modes as candidates for fusion power plants was made. Five different regimes of operation were considered: (1) steady-state operation in the first-stability regime, *e.g.*, ARIES-I¹⁹, (2) steady-state operation in the second-stability regime, *e.g.*, ARIES-II and ARIES-IV²⁰, (3) pulsed-plasma tokamak operation, *e.g.*, Pulsar²¹, (4) steady-state operation with reversed-shear profile, and (5) low-aspect ratio tokamaks (spherical tokamaks). The extent of the plasma physics data base as well as performance as a power plant were considered.

Earlier studies have shown that optimum, steady-state first-stability tokamaks have moderately high plasma aspect ratio ($A \equiv 1/\epsilon \sim 4.5$) and low plasma current ($I_p \sim 10$ MA) at relatively high poloidal beta ($\epsilon\beta_p \sim 0.6$) in order to reduce the current-drive power by maximizing the bootstrap current fraction, f_{BS} . The maximum bootstrap fraction in this class is about $\sim 70\%$ with most of the driven current located near the magnetic axis. However, the important parameter $\epsilon\beta_p$ is related to achievable plasma β through

$$(\epsilon\beta_p)(\beta/\epsilon) \leq (\beta_N/20)^2 S \quad (1)$$

where $S = (1 + \kappa^2)/2$ is the plasma shape factor, κ is the plasma elongation, and β_N is defined by $\beta \leq \beta_N(I_p/BTa_p)$. For a conventional first stability configuration (similar to PULSAR) with high current (low edge safety factor, q_*), optimally shaped current and pressure distributions, and with sufficient triangularity in the cross-sectional shape, this equation must be obeyed with a Troyon coefficient of $\beta_N = 3.5$. Plasma configurations with non-optimal profiles and shapes can be unstable at values of β_N lower than 3.5. If a high f_{BS} is desired for steady state operation (such as ARIES-I), one can reduce the current or raise q_* , resulting in a lower β . Therefore, optimum first-stability tokamak discharge have $\beta \simeq 2\%$, and still requires ~ 100 MW of current-drive power. There is ample experimental data base for this regime, however, operation in discharges with durations longer than the current diffusion time is needed.

Pulsed-tokamak power plants avoid the problem of non-inductive current drive, the constraint on β_p is removed and plasma β can be higher. Also, the recirculating power for current drive is eliminated. However, inductive current-drive also imposes certain constraints on the plasma operating regime. Because the loop voltage is constant across the plasma, the current-density (induced and bootstrap)

and pressure profiles are set for a given pair of density and temperature profiles. In principle, because the current-density profiles cannot be tailored, both the normalized β value and bootstrap fraction are limited ($\beta_N \sim 3.0$, $f_{BS} \lesssim 40\%$). In addition, many critical engineering issues have to be resolved. For example, cyclic fatigue becomes a major issue limiting the maximum toroidal field. This decrease in the toroidal-field strength more than offsets the gains in plasma β values for a pulsed device, resulting in a lower fusion-power density and a larger tokamak relative to a steady-state design. Large and expensive poloidal-field coils also are needed and this constraint leads to the desire of a moderately high-aspect ratio, low-current plasma. An innovative, sensible-heat storage system in the outer shield was developed for the PULSAR design which removed the cost of energy-storage as a barrier to pulsed-tokamak power plant. As a whole, pulsed power plants are substantially more costly than steady-state ones. On the other hand, this regime of operation is supported by the main body of tokamak experimental data.

As is seen from Eq. (1), the only way to increase the plasma β and still have a large bootstrap current fraction is to increase the value of β_N . It may be possible to violate the Troyon limit if certain conditions are met such as through elevated central safety factor ($q_0 \geq 2$)¹⁴ as in ARIES-II/IV designs, reversed magnetic shear^{15,16}, or at very low aspect ratios¹⁷. In addition to these requirements, stabilization of the external kink mode in a second stability plasma requires a close fitting conducting wall and sufficient plasma rotation¹⁸.

Second-stability operation allows for higher bootstrap current fraction than first-stability operation. While bootstrap current can become as large as the total plasma current, the profile is different than that needed for equilibrium and stability. As a result, current should be driven both on the axis and at the plasma edge while cancellation of part of the bootstrap current in the middle of the plasma may be required. Essentially, the optimum configuration has bootstrap current fraction of $\sim 90\%$ and, compared to the steady-state, first-stability optimum regime, the current-drive power is somewhat smaller and the plasma β is about twice as large (a conducting wall for stabilization of kink modes is required). The critical issues for this regime of operation include startup and access to the second-stable operating point, as well as complexity of the current drive system. In addition, there is very little experimental evidence for this mode of operation.

Reversed-shear plasma operation combines the best features of steady-state, first- and second-stability modes. There is a much better match between the bootstrap current-density profile and that needed for equilibrium and stability and, therefore, higher values of plasma β can be achieved with moderate current-drive power and less complicated current-drive system. There is ample theoretical

research on this regime and some experimental data base is available. An extensive experimental exploration of this regime of operation is currently on-going.

Operation at a low plasma aspect ratio (low-aspect ratio or spherical tokamaks) is another approach to achieving high plasma β and a high bootstrap current fraction. Unfortunately, the low aspect ratio of plasma rules out the use of superconducting toroidal-field coils as there is not enough space for a large shield in the inboard. Therefore, a low-aspect-ratio tokamak requires equilibria with a very high plasma β (in order to minimize the Joule losses in the center-post). In addition, because the plasma current is very large (~ 30 to 40 MA) in a low-aspect-ratio tokamak, a very high bootstrap current which is also well-aligned to the equilibrium current profile is essential (to minimize current-drive power). Detailed MHD equilibrium and stability and current drive calculations have been performed and some promising equilibria have been produced. This regime of operation offers unique features and is currently pursued vigorously in the physics community. However, the design activity has not reached the level of maturity needed to make a sound assessment of the performance of spherical tokamaks as power plants. Our assessment, therefore, has focused mostly on existing designs and several critical issues in the design and center-post and engineering systems also have been identified and discussed in the next section (see also Ref. 2, 7, 12).

A system assessment of the above five candidates for tokamak plasma regime of operation has been performed^{2,7}. Based on the economic performance (to satisfy the economic requirements) and the degree of maturity of the concept, the Starlite project has chosen reversed-shear operation for its reference design.

III. ENGINEERING OPTIONS

The range of design options for fusion power plants is limited, and has been examined in numerous studies during the past 25 years. Previous studies have shown that advanced low-activation ferritic steel, vanadium alloy, or SiC/SiC composites are the most credible candidates for the primary in-vessel structural material. An assessment of engineering design options has been performed using these three materials and the associated in-vessel component designs which are compatible with them.

Ferritic Steel Designs

Unlike vanadium and SiC composites, ferritic steel is compatible with several different coolants, and can be used effectively with either solid ceramic breeders or liquid metals. Steel is by far the most developed material option, such that the database is also most developed. Intimate knowledge of the limitations of this class of alloys must be

balanced against the sometimes large uncertainties which exist in the behavior of V-alloys and SiC/SiC composites.

Four aspects of the top-level mission requirements have been given special attention in the assessment: maintainability, thermal conversion efficiency and performance limitations (which impact cost), a cost assessment of the trade-off between material costs *vs.* performance, and activation. These were determined to be most significant as discriminators between the various design options.

Two key issues were selected for special attention: consequences of the loss of ductility and ferro-magnetism effects. Ductility is viewed as the most serious concern. Ferro-magnetism causes important operational problems, but these were viewed as solvable if an appropriate R&D program were carried out.

The results of the assessment indicate that ferritic steel remains a potential power plant structural material within a certain restricted range of performance⁸. The requirements for waste disposal are likely to be met with low-activation variants of ferritic steel, such that this was not considered to be a major discriminating factor. Its ability to meet the minimum requirement for competitive cost of electricity is one of the most serious concerns. The relatively restricted temperature range of operation and relatively low thermal conductivity limit the fusion core power density and the plant thermal conversion efficiency, leading to larger machines with more restrictive power density limits. In addition, it is highly unlikely that steel could be used in the divertor unless the heat flux can be maintained much lower than current projections. In that case, an alternate technology must be identified, further complicating the system. Safety implications of ferritic steel were not adequately assessed, and should be given special attention in future studies.

Ferritic steel components have fewer critical issues as compared with other material candidates. However, the loss of ductility under irradiation is potentially a feasibility issue. Existing irradiation experiments performed in the temperature range of 250-400 °C in mixed-spectrum reactors result in ductile-to-brittle transition temperature (DBTT) values of about 250 °C under conditions with simultaneous neutron damage and helium generation. Similar testing in fast reactors at $T \geq 365$ °C with neutron damage, but very little helium production, results in DBTT < 0 °C for some alloys. Without fully understanding the role of He in raising the DBTT, it is difficult to extrapolate these results to a fusion-reactor spectrum which is characterized by about 10 appm-He/dpa at the plasma surface of the first wall. What is clear, however, is that special precautions would be required if ferritic steels embrittle in a fusion reactor as they do in a mixed-spectrum reactor, and the risk of failure may be significantly higher in power plants which use a brittle structural material.

Vanadium Designs

Vanadium alloys have been included in many fusion R&D programs throughout the world due to their potential for improved thermomechanical performance, safety advantages, and possibly longer lifetime. The use of vanadium restricts the use of other materials (such as the coolant and breeder) due to compatibility. Design options using both lithium and helium as coolant were considered. The assessment of blanket options concentrated on the use of lithium as breeder. Lithium offers the best opportunity for high power density operation, and has unique compatibility features with vanadium alloys. Two coolant options were considered: self-cooled lithium and high-pressure helium. Several previous design studies, such as ARIES-II²⁰ detailed descriptions of the self-cooled concept. The He-cooled blanket option is relatively less studied. Liquid PbLi is a possible candidate for the breeder and/or coolant, but U.S. R&D programs do not currently support this option.

Three power plant requirements were selected for more detailed examination. First, the high cost of vanadium is a major concern. The improved performance must offset the higher capital and replacement costs for the in-vessel components. Strategies for minimizing the quantity of vanadium, maximizing the lifetime and replacing (or recycling) components have been addressed. Second, accident safety and waste management were examined to determine whether the aggressive Demo requirements can be met. Finally, reliability and availability were briefly surveyed. All design concepts will have a difficult development path to meet the very stringent utility requirements on availability.

Three of the critical issues associated with the use of vanadium were examined. The materials data base for vanadium alloys is small, but growing. Some of the important material-related issues include tensile and creep behavior under irradiation, compatibility with coolants and breeders, and fabrication. Tritium recovery and control is the second issue examined. Recovery methods from lithium have been developed, but the stringent requirements for impurity control (to prevent degradation of the vanadium properties) leads to special concerns. Finally, the possibility of vanadium recycling was explored as a means to offset the high cost of the material.

While uncertainties in the potential attractiveness of vanadium systems is acknowledged, it was decided to develop the V-Li system for the detailed conceptual design phase which followed these assessments. The ultimate potential of fusion depends on our ability to provide high performance systems with minimal safety and environmental impacts. Vanadium appears to offer the potential to meet this challenge.

SiC Composite Designs

SiC composite material with a projected allowable temperature capability $\geq 1000^\circ\text{C}$ was selected as the structural materials for ARIES-I¹⁹ and ARIES-IV²⁰ reference designs. These designs have been used as the basis for assessing the advantages and issues associated with a possible Demo power plant based on SiC composites as the primary in-vessel structural material.

To take full advantages of the low activation and high temperature capability of SiC composite material, 5–10 MPa helium was used as the coolant. The ARIES-I design used Li_2ZrO_3 as the solid tritium breeder, Be metal sphere-pac as the neutron multiplier, and W as the divertor coating material. Due to the induced activation of Zr and W, the safety rating of this design is Level of Safety Assurance (LSA) = 2. Based on new experimental results, Li_2O was used as the solid breeder for the ARIES-IV design. If the use of W can be avoided as the plasma facing components (PFC) coating material, then an inherently safe design of LSA-1 can be obtained. This also assumes that the Be chemical energy and toxicity concerns are eliminated. The ARIES-IV design satisfy all of the neutronics and thermal hydraulic performance requirements of Demo. We also found that by increasing the helium pressure to about 12 MPa, and taking advantages of the improved recuperator performance of the closed cycle gas turbine system, at a helium outlet temperature of about 950°C , a gross thermal efficiency of about 55% can be expected.

In the evaluation of the use of SiC-composite as the structural material for the Demo design, there was no doubt of its projected benefits; the key question is on whether its development schedule can meet the projected schedule of Demo (assumed to be 2025). Key issues for the application of SiC composite are in the areas of material development that can match the schedule of the US Demo design, the behavior of the composites in a fusion environment, the need for electrical-conducting components to stabilize the plasma, and the development of robust PFCs. Fundamental improvements in material irradiated properties, such as thermal conductivity, are needed, for example by using advanced SiC fiber and interface materials. Other material development issues include economic fabrication of large SiC-composite components, development of vacuum leak tight components, the technique of brazing ceramic parts, and the development of the joining techniques of SiC composite to metallic parts.

IV. ISSUES SPECIFIC TO LOW-ASPECT-RATIO TOKAMAKS

The assessment of low-aspect-ratio tokamak power plants included detailed physics calculations, system studies, and preliminary engineering design considerations. The physics

analyses yielded equilibria that are stable to all MHD modes (with a wall present) and require very little current drive power ($\lesssim 10$ MW) due to bootstrap fractions approaching unity. These equilibria had the following characteristics: aspect ratio of 1.25, elongations of 3 and β as high as 40%. It is noted that these cases would require a conducting wall to stabilize the external kink mode. The sensitivity of the current drive power requirements to variations in plasma profiles is an important issue and must be addressed in future studies. Using the cases noted above, system studies and engineering analyses were conducted. A major conclusion of the system studies was that, even for these cases with low current-drive power requirements, there still was significant recirculating power (*i.e.*, recirculating power fraction ~ 0.6) associated with the resistive losses in the copper center post and return legs of the toroidal field coils. Because of the high-recirculating power fraction, the low-aspect ratio tokamak is quite sensitive to choice of plasma β , design of the center-post, and detail analysis of the current drive requirements. Other studies suggest lower values of recirculating power fraction in a low-aspect ratio power plants. The true potential of a low-aspect ratio tokamak power plant can only be assessed after a comprehensive design study.

Minimizing the amount of inboard shielding for the low-aspect-ratio tokamak is well known to be an important factor. There are three main concerns with an unshielded center-post: (1) transmutation of the copper in an unshielded center-post increases the electrical resistivity of the center-post; (2) copper loses its ductility under irradiation making the mechanical design difficult, (3) activation levels in an unshielded copper center post exceeds the U.S. NRC Class-C low-level waste-disposal limit after a few weeks. Our systems and engineering analyses indicated about 30 cm of shielding to the center post would resolve the above concerns.

In addition to concerns about the design of the center post, preliminary engineering evaluations also identified constraints with regard to the blanket and divertor. The high fusion power density of a low-aspect-ratio tokamak limits the choice of blanket and in-vessel component design. In the context of blanket design, the use of water in the center-post makes the use of liquid lithium in the blanket problematic due to safety issues. Additional barriers to leakage would be necessary and substantial additional analysis would have to be performed to satisfy licensing and regulatory requirements if liquid lithium were to be used in the blanket. If liquid lithium is ruled out as a coolant, the overall thermal conversion efficiency of the blanket would be much lower and further reduces the overall plant efficiency which is already low ($\sim 17\%$). Finally, the divertor problem appears especially severe for the low-aspect-ratio tokamak concept because the divertor surface area available at low major radius is so restricted.

V. SUMMARY AND CONCLUSIONS

Through its successful operation, the Fusion Demo must be sufficiently convincing that a utility or independent power producer will choose to purchase one as its next electric generating plant. A fusion power plant which is limited to the use of currently-proven technologies is unlikely to be sufficiently attractive to a utility unless fuel shortages and regulatory restrictions are far more restrictive to competing energy sources than currently anticipated. In that case, the task of choosing an appropriate set of physics regime of operation and engineering technologies **today** involves trade-offs between attractiveness and technical risk. In general, more advanced concepts appear more attractive but entail critical issues which must be addressed by R&D programs prior to a commitment to construct the Demo.

A systematic approach to trade-offs between attractiveness and technical risk was developed for the Starlite project. First, a set of quantifiable top-level requirements, and goals for both commercial fusion power plants and the Fusion Demo were developed. Next, several candidate options for physics operation regime as well engineering design of various components (*e.g.*, choice of structural material, coolant, breeder) have been developed and assessed. In each area, this assessment was aimed at investigating (1) the potential to satisfy the requirements and goals, and (2) the feasibility *e.g.*, *critical issues* and credibility (*e.g.*, degree extrapolation required from present data base). This assessment led the choice of the reversed-shear as the plasma operation regime and a self-cooled lithium design with a hybrid system including vanadium alloy for in-vessel and blanket structures, and other material for shield¹¹ for the detailed design.

REFERENCES

1. L. Waganer, F. Najmabadi, and M. S. Tillack, "What Must Demo Do?" *Proc. IEEE 16th Symp. on Fusion Eng.*, Champaign, IL (Oct. 1995).
2. F. Najmabadi *et al.*, "The Starlite Project—Assessment Phase Report," University of California, San Diego report UCSD-ENG-005 (1996).
3. J. Kaslow *et al.*, "Criteria for Practical Fusion Power Systems - Report from the EPRI Fusion Panel," EPRI report BR-104469 (1994).
4. R. Miller *et al.*, "Starlite Economics: Requirements and Methods," *Proc. IEEE 16th Symp. on Fusion Eng.*, Champaign, IL (Oct. 1995) (to be published).
5. J. Clarke, "Environmental Issues and Global Energy Economy Project," *Proc. IEEE 16th Symp. on Fusion Eng.*, Champaign, IL (Oct. 1995) (to be published).
6. R. L. Miller, "Fusion Power Plant Economics," *these proceedings*.
7. C. G. Bathke *et al.*, "A Systems Assessment of the Five Starlite Tokamak Power Plants," *these proceedings*.
8. M. S. Tillack *et al.*, "Analysis of the Tradeoff between Improved Performance and Increased Cost of Advanced Materials," *these proceedings*.
9. D.-K. Sze *et al.*, "Blanket Selection for the Starlite Project," *these proceedings*.
10. L. Bromberg, O. Titus, *et al.*, "Innovative Out-of-Plane Support of TF Coils and Implication to Fusion Core Maintenance," *these proceedings*.
11. L. A. El-Guebaly, C. G. Bathke, *et al.*, "Cost-Effective Shield Design for Environmentally Attractive Fusion Power Plants," *these proceedings*.
12. L. A. El-Guebaly, H. Y. Khater, *et al.*, "Initial Nuclear Assessment for a Low Aspect Ratio Tokamak Power Plant," *these proceedings*.
13. L. Bromberg, M. Sidorov, "Busbar for the Low-Aspect-Ratio Tokamak Device," *these proceedings*.
14. J. J. Ramos, "Theory of the Tokamak Beta Limit and Implications for Second Stability," *Phys. Fluids B* **3** (1991) 2247.
15. T. Ozeki *et al.*, "Profile Control for Stable High- β_p Tokamaks with Large Bootstrap Current," *Proc. 14th Int. Conf. on Plasma Phys. and Controlled Nucl. Fusion Research*, Würzburg, Germany (Oct. 1992), International Atomic Energy Agency, Vienna (1993).
16. C. E. Kessel *et al.*, "Improved Plasma Performance in Tokamaks with Negative Magnetic Shear," *Phys. Rev. Lett.* **72** (1994) 1212.
17. J. Menard *et al.*, "Ideal MHD Stability of High Beta/High Bootstrap Fraction Equilibria in NSTX," *Bull. Am. Phys. Soc.* **40** (1995) 1655.
18. A. Bondeson and D. J. Ward, "Stabilization of External Modes in Tokamaks by Resistive Walls and Plasma Rotation," *Phys. Rev. Lett.* **72** (1994) 2709.
19. F. Najmabadi, R. W. Conn, *et al.*, "The ARIES-I Tokamak Reactor Study—Final Report," University of California, Los Angeles report UCLA-PPG-1323 (1991).
20. F. Najmabadi, R. W. Conn, *et al.*, "Directions for Attractive Tokamak Reactors: The ARIES-II and ARIES-IV Second-Stability Designs," F. Najmabadi, R. W. Conn, *et al.* *Proc. 14th Int. Conf. on Plasma Phys. and Controlled Nucl. Fusion Research*, Würzburg, Germany (Oct. 1992), International Atomic Energy Agency, Vienna (1993).
21. F. Najmabadi *et al.*, "The PULSAR Study—A Pulsed-Tokamak Fusion Power Plant," University of California, San Diego report UCSD-ENG-003 (1996).