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Lessons Learned from the Tokamak Advanced Reactor Innovation and Evaluation Study (ARIES)

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ABSTRACT

Lessons from the four-year ARIES (Advanced Reactor Innovation and Evaluation Study) investigation of a number of commercial magnetic-fusion-energy (MFE) power-plant embodiments of the tokamak are summarized. These lessons apply to physics, engineering and technology, and environmental, safety, and health (ES&H) characteristics of projected tokamak power plants. A general conclusion from this extensive investigation of the commercial potential of tokamak power plants is the need for combined, symbiotic advances relative to present understanding in physics, engineering, and materials before economic competitiveness with developing advanced energy sources can be realized. Advanced tokamak plasmas configured in the second-stability regime that achieve both high β and bootstrap fractions near unity through strong profile control offer high promise in this regard.

I. INTRODUCTION

A. Scope of Assessment

A compilation of "bottom-line" lessons derived from the four-year ARIES (Advanced Reactor Innovations Study) and an assessment related thereto are reported. This assessment is made by key members of the ARIES systems-studies team,[1] but does not represent an ARIES Projects consensus; this systems assessment, however, benefited from review and critique from many Project members. A focus is placed on the economic, safety, and environmental impacts of key physics, engineering, materials, and operational assumptions that form the bases of the ARIES tokamak power-plant conceptual designs. It is well recognized that attributes other than (quantifiable) cost, even if the cost being assessed reflects credits for nuclear-safety characteristics that are unique to fusion, can be listed as reasons for developing fusion power (*e.g.*, elimination of CO_2, reduced mining, eased nuclear licensing, unlimited fuel supply, *etc.*); however, even these attributes must eventually be expressed on a common costing basis for informed choices to be made. Although these social, technical, and economic aspects of each ARIES design are recognized, they were not included as a quantitative task for ARIES, and, hence, are not explicitly treated in this summary assessment. Exclusion of these issues from this assessment, however, does not diminish their importance to this cost-based assessment and to any future projection of form and role for fusion.

Throughout this assessment "economic competitiveness" is measured against an advanced (nuclear) energy system that is assumed: a) to be accepted by the (U.S.) public; b) to be licensed in an acceptable period of time; and c) to have developed and implemented a safe and economic means for radioactive waste disposal. These assumptions also largely apply to ARIES. While progress is being made in these areas, complete resolution of these issues is not in hand. If these four key issues cannot be resolved for advanced fission power, then fusion through exploiting unique ES&H characteristics may find a competitive edge (*i.e.*, point of market penetration) by offering an opportunity for enhanced public acceptance, reduced licensing burden, generation of more acceptable waste forms, and an economic "closure" of the nuclear fuel cycle. The means used in ARIES to quantify in economic terms this "ES&H edge" are primarily limited to safety, and are reflected in subsystem cost credits if certain "Levels of Safety Assurance" (LSA) could be designed and demonstrated, recognizing that expensive, unconventional materials may be required. In addition, some of the less-quantifiable ES&H issues listed above are incorporated indirectly into the ARIES costing through the assumptions of short construction time (*i.e.*, 6 yr) and a relatively low Decommissioning and Decontamination (D&D) charge. If, however, these potential ES&H advantages do not come to fruition for economic reasons or because advances in fission obviate most of the important ES&H differences between fission and fusion power, then a more symbiotic role must be considered for fusion in the overall energy strategy.

The level of understanding and the models available to ARIES fall somewhat short in quantifying many of the important issues listed above. This assessment obviously must work with the tools and results that are available. Hence, the focus of this summary and assessment is the examination and interpretation through cost-based object functions of physics and engineering interconnectivity that has led to the ARIES economic projections and the direction in both physics and engineering where improved projections for the tokamak power plant might be found. Detailed technical assessments of each ARIES design are given in Ref. 2.

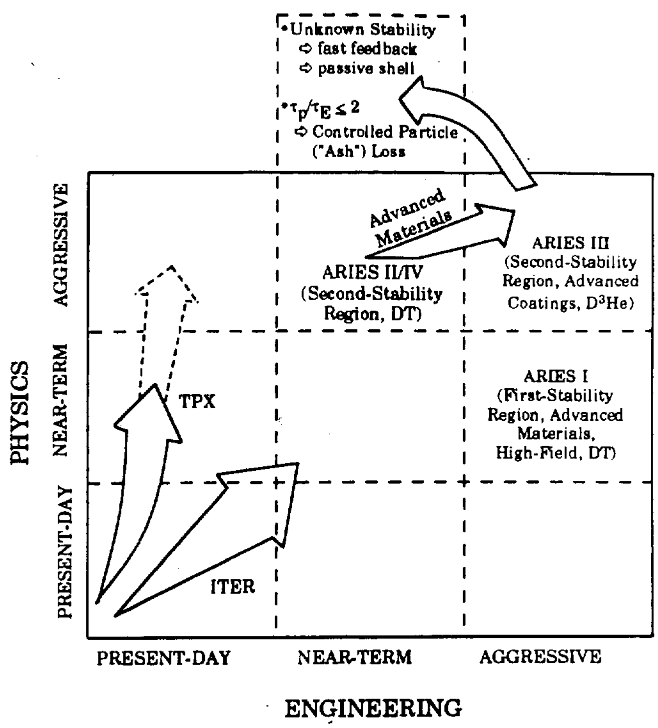


Fig. 1. Physics-Engineering configurational space used to target goals and objectives for each ARIES design.

B. ARIES Background

A range of tokamak reactor concepts was considered by ARIES in a series of sequential studies identified as ARIES-I, -III, and -II/IV. Each study explored the impact of different sets of assumptions on the degrees of extrapolation from the present physics and/or engineering bases needed to achieve each tokamak reactor embodiment. The general goal of the ARIES project was to assess the economic competitiveness, level of safety assurance, and environmental features that could be obtained in tokamak-based fusion power plants under varying levels of engineering and physics extrapolation from present experience. The scope and goals of each of the ARIES designs are illustrated graphically in Fig. 1, which depicts an Engineering-Physics "phase space".[3] Each design is located in this phase space by a qualitative measure of the required in either Physics or Engineering.

Even though the metric used in Fig. 1. is subjective, this matrix proved useful in defining, guiding, and executing the project. This matrix also remains useful for characterizing the ARIES designs that resulted. The location of each ARIES design has been assessed before and after each design study, and the related shifts are indicated; Also illustrated schematically on Fig. 1 are the R&D trajectories for both ITER[7] and TPX[8], with both the Physics and Engineering goals for each being assumed to be achieved through a relatively short R&D period with high confidence.

All ARIES studies constrained tokamak operation to steady state, thereby necessitating non-inductive plasma current drive; this constraint was a major driver in establishing the size, physics parameters, and technologies for all ARIES designs. The studies were periodically updated and normalized throughout the project by closely coupled cost-based systems analyses to facilitate common-basis comparison of the ARIES studies and to assure the benefits of lessons derived from one study could be applied to ARIES studies previously completed or (at that time) in progress.

II. DESIGN SUMMARIES

Figure 2 compares the fusion-power-core (FPC) profiles of the four final ARIES designs with a Pressurized-Water (fission) Reactor (PWR) of comparable capacity[9]. The ARIES-I′ and -III′ designs shown in Fig. 2. include improvements and/or refinements developed and applied at the systems-studies level (*i.e.*, without subsequent conceptual engineering (re)design) after publication[4,5] in the ARIES-II/IV study. Table II

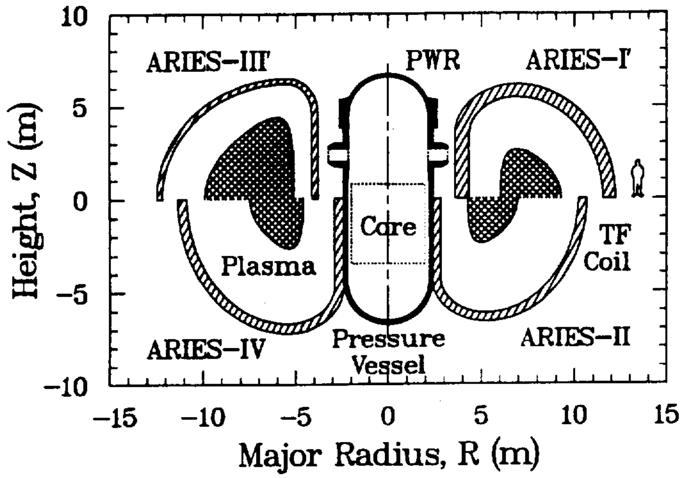


Fig. 2. Fusion-Power-Core (FPC) cross sections for the final 1-GWe ARIES designs.[6] A Pressurized-Water fission Reactor (PWR) of comparable (1.1 GWe) net-electric power is also shown.[9]

summarizes key features for each of the ARIES designs, along with figures-of-merit for safety and economic characteristics. The cost of electricity (COE, mill/kWeh) was used as the object function to optimize the physics- and technology-constrained designs. Capital-cost credits were awarded when material and configurational choices gave some assurance that the nuclear risk from accidental releases might be reduced; the disposal cost of all radioactive wastes were included as part of an incremental COE attached for D&D purposes.

A. ARIES-I/ARIES-I′

The ARIES-I design was completed in 1990 and is a DT-fueled reactor that would rely on modest improvements from present-day physics results based on the first-stability regime (FSR) of plasma performance. The required technologies, however, are significantly more advanced than those available today, particularly in the areas of advanced low-activation materials, efficient radiofrequency power systems, and advanced high-field superconducting magnets. Those ARIES-I design features that would maximize the environmental and safety attributes of fusion were emphasized.

The direct costs of major power-plant accounts, the direct costs of key FPC subaccounts, and the cost of electricity are shown in Fig. 3, which also includes a comparison of the projected COE with a range of fission and fossil (coal) power stations[11] that have been normalized to the same net-electric capacity (P_E = 1,000 MWe) and year (1992). While the IPWR, APWR-MU, and Coal-MU designs (re: Fig. 3.) minimize the capital-return component of the COE at ~ 28 mill/kWeh, the inherently more massive FPC requires

TABLE I. Summary of 1-GWe ARIES Tokamak Power-Plant Designs [a]

ARIES	I′	II	III′	IV
FUEL CYCLE	DT	DT	D-^{3}He	DT
GEOMETRY				
Major radius, R_T (m)	7.64	5.60	7.5	6.04
Minor radius, a (m)	1.70	1.40	2.50	1.51
Vertical elongation, κ	1.80	2.03	1.84	2.03
Aspect ratio, $A = R_T/a$	4.5	4.0	3.0	4.0
PHYSICS				
MHD stability regime[b]	FSR	SSR	SSR	SSR
Edge safety factor, q	4.5	12.2	6.9	12.2
Plasma beta, β	0.019	0.034	0.24	0.034
Temperature, T_i (keV)	20	10	55	10
Density, n_e (10^{20}/m^3)	1.26	2.50	3.17	2.90
Confinement factor,[10] H	2.7	3.1	7.2	3.1
Radiation fraction, f_{RAD}	0.50	0.18	0.67	0.23
Plasma current, I_ϕ (MA)	10.9	6.43	29.9	6.64
Bootstrap fraction, f_{BC}	0.68	0.87	0.75	0.87
Gain, $Q_p = P_F/P_{CD}$	17.8	28.9	16.3	29.8
BLANKET/SHIELD				
Coolant	He	Li	OC[c]	He
Structure	SiC	V5Cr5Ti	HT-9M	SiC
Tritium breeder	Li_2O	Li	–	Li_2O
Neutron multiplier	Be	–	–	Be
Shield	SiC	Tlon[d]	Fe-1422	SiC
MAGNETS(Nb_3Sn)				
TF-coil peak field, $B_{\phi c}$ (T)	19.1[e]	15.9	14.0	15.9
Magnetic energy, W_B (GJ)	213	83	169	93
Specific energy, W_B/M_c (MJ/kg)	42	34	55	34
REACTOR PERFORMANCE				
Thermal efficiency, η_{TH}	0.49	0.46	0.44	0.49
Engr. gain,[f] $Q_E = \epsilon^{-1}$	4.66	6.49	4.28	5.20
Wall loading, I_w (MW/m^2)	2.1	2.9	0.08	2.67
Mass Power Density, MPD = P_E/M_{FPC}(kWe/tonne)	71.7	92.6	88.8	111.0
Level of Safety Assurance, LSA[g]	1	2	2	1
COSTS (Constant-1992 $)				
Unit Total Cost, UTC ($/We)	4.40	4.17	4.24	3.67
COE (mill/kWeh) w/o LSA	101	84	99	90
COE (mill/kWeh) w/ LSA	77	74	89	68
capital return	64	61	62	53
O&M	7	9	9	8
blanket replacement	5	4	0.01	7
decommissioning	0.25	0.5	0.5	0.25
fuel	0.03	0.03	18	0.03

[a] Detailed parameter listing and comparison in Ref. 1
[b] FSR = First Stability Regime; SSR = Second Stability Regime
[c] OC = organic coolant (mixed teraphenyls).
[d] Tennelon (a manganese steel)
[e] uses advanced, ternary Nb_3Sn.
[f] $\epsilon = P_c/P_{ET}$, fraction gross electric power recirculated
[g] LSA = 1 inherently safe; LSA = 4 needs active safeguards

nearly twice as much capital return for ARIES-I/I′. The higher capital costs for fusion cannot be offset by the reduction in fuel costs in proceeding from fossil to fission to fusion. However, the first-wall, blanket, and reflector replacement costs incurred only in fusion can be comparable to the fuel costs for fission. The O&M costs are comparable for all energy sources. The direct costs, which are approximately half of the total costs, for the fusion cases considered are dominated by the reactor-plant-equipment costs, which in turn are dominated by the FPC costs. Approximately 85 % of the FPC costs reside in the first wall, blanket, and shield; the magnets; and the current-drive system. In the DT-fueled ARIES-I/I′ (as well as ARIES-II/IV) the first-wall, blanket, and shield costs comprise 43-47 % of the FPC costs.

B. ARIES-III/III′

The ARIES-III design was initiated in 1990 out of numerical sequence with the ARIES-II/IV second-stability-region (SSR) designs to force an early assessment of D-^{3}He and the impact of reduced neutron production in a tokamak fusion reactor. Completed in 1991, the D-^{3}He-fueled ARIES-III design requires a level of plasma performance that is significantly more advanced than is required to fuse DT, but a significant reduction in neutron production and subsequent radioactivity generation in structural materials was anticipated. Furthermore, the reduced neutron environment makes possible a simpler shield (a tritium-breeding blanket *per se* is not required) that is designed to recover only heat and to protect the magnets, while using materials and coolants generally not applicable for use in the intense neutron fluxes associated with DT-fueled system. An important goal met by the D-^{3}He-fueled system is a fusion power core that operates for the life of the plant.

The neutron production from the side reactions occurring in the D-^{3}He fuel cycle caused sufficient structural activation of the HT-9M alloy used and, along with the chemical energy stored in the low-pressure organic coolant (OC), held the safety rating to that of the DT-fueled ARIES-I design. Re-analysis of ARIES-III indicated that the organic coolant could be exchanged for pressurized water to enhance the LSA rating to 1, but the decrease in thermal-conversion efficiency (from 44 % to 35 %) slightly overrode the increased-LSA cost credit to raise the COE by ~ 1 mill/kWeh[12]. After an extensive assessment of FSR tokamak physics, the use of SSR advanced-tokamak physics was invoked, because the projected COE was 20% lower. Even with advanced-SSR physics, however, the level of plasma performance required steps that are possibly beyond

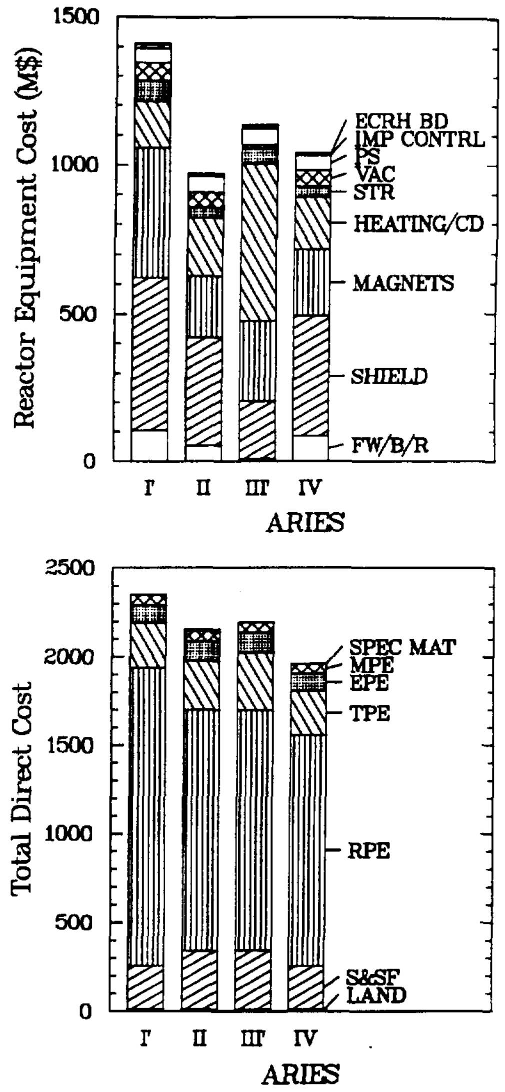
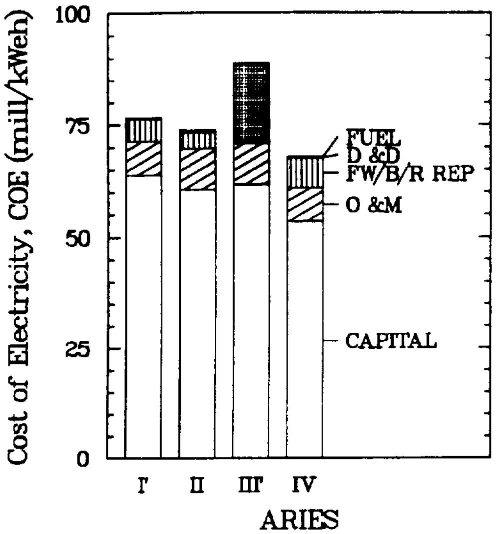


Fig. 3A. Histogram of direct costs for key Fusion-Power-Core (FPC) components and main power plant subsystems for all ARIES (final, normalized) designs.

the "Aggressive" categorization, as is indicated on Fig. 1. The final (cost) optimization of ARIES-III suggested a less-advanced coil technology was more economical for a peak TF-coil magnetic field of 14 T and, along with the final selection of fairly conventional HT-9M blanket structure cooled by organic liquid suggested an Engineering reclassification from "Aggressive" to "Near-Term" (Fig. 1).

C. ARIES-II/IV

The ARIES-II and -IV studies were conducted concurrently, with both being completed in late 1992. These DT-fueled reactors invoke the same (SSR)



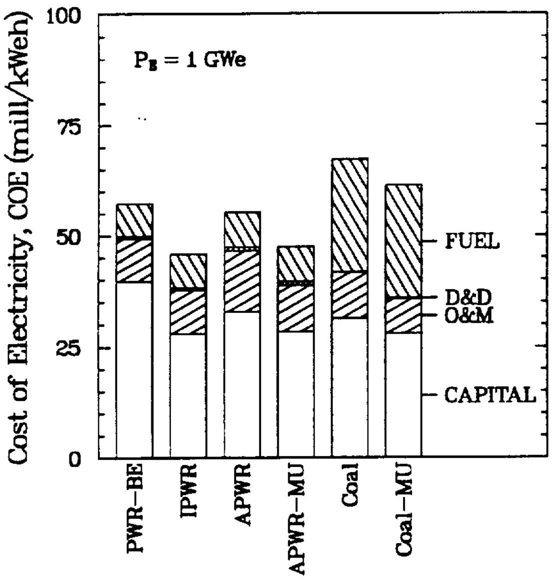


Fig. 3B. Histogram of the Cost-of-Electricity (COE) values projected for both ARIES and a range of fossil and fissile power stations[11] of comparable capacity P_E = (1.0-1.2 GWe, scaled to P_E = 1,000 MWe) in Constant-1992 Dollars. (IPWR = Improved Pressurized-Water Reactor, APWR-MU = Advanced Pressurized-Water Reactor - Multiple Units)

plasma performance that is more advanced than assumed for ARIES-I but is less extrapolative than for ARIES-III. The main benefits of SSR plasmas, as applied to ARIES-II/IV, are promises of reduced plasma current and bootstrap-current fractions approaching unity at increased stable β. The ARIES-II study used a blanket system based on vanadium alloy structure cooled by liquid lithium, while the ARIES-IV study invoked a low-activation silicon-carbide composite structure cooled by high-pressure helium. The ARIES-IV blanket is a refinement of the ARIES-I blanket in that the ARIES-I neutron-activating tritium-breeder, Li_2ZrO_3, was replaced with Li_2O, which requires less beryllium neutron multiplier; these refinements have important cost and safety impacts. A comparison of FSR and SSR from the ARIES-II/IV studies concluded that the improved plasma performance of SSR relative to FSR decreased the projected cost of electricity by 19 %. The improvements, however, were not as significant as anticipated from projections based on ARIES-III physics results. The ARIES-II and -IV designs would not be competitive economically with advanced fission power plants (*i.e.*, 55 and 42 % more expensive in projected cost of electricity, respectively). Furthermore, application of blanket and magnet improvements used in ARIES-IV to the sister ARIES-I concept reduced the COE differences between the two from 50 % to 13 %; the FSR, however, is 21% more expensive than the SSR tokamak. Although the use of special FPC materials in both ARIES-II(V/Li) and ARIES-IV(SiC/SiC/He) was classified as a "Near-Term" Engineering requirement, application in the large sizes and high (neutron) radiation fields of ARIES-II/IV could cause an increase in the already "Aggressive" Engineering requirement, as is suggested in Fig. 1.

III. KEY FINDINGS AND LESSONS

The findings from the ARIES project are presented here as a composite derived from each of the ARIES studies.

A. General Findings

1. Relative to fissile- or fossil-fuel electrical power generators, tokamak fusion systems studied by ARIES have higher recirculating powers, convert heat to electricity with the same (high) efficiency as fissile and fossil power plants, but generally heat generation occurs in a more massive, higher-technology system: the net result for tokamak fusion is higher capital costs that are caused both by a more expensive heat generator and the need for an expanded fusion-power-core balance-of-plant systems required to provide internally recirculated power. Although fuel costs (for terrestrially available DT) are significantly reduced relative to fission, the first-wall and blanket replacement costs, which are analogous to present fission fuel-cycle costs (*e.g.*, without chemical reprocessing), can be comparable. The cost credits related to reduced nuclear hazard (through LSA credits) and waste generation (absorbed in a relatively low D&D charge) were not sufficient to reduce COE, for the range of steady-state tokamak

power plants studied by ARIES, to values comparable with present projections of advanced fission power.

2. An economic balance forces compromise between engineering gain ($Q_E = 1/\epsilon$, determined primarily by current-drive power) and FPC capital cost [indirectly, the mass power density, $MPD(kWe/tonne)$, Table I]. Both the shape and location of economic optima resulting from this balance to maximize both Q_E and MPD depend sensitively and often unintuitively (*e.g.*, results from multi-variable, constrained optimizations) on specific physics and engineering constraints, component unit costs, plant capacities, material choices, and resulting safety-related cost reductions; the four tokamak power-plant designs examined in ARIES illustrate the impact of these constraints in generating the variability of economic balances between Q_E and MPD; interestingly, all ARIES designs cluster close to each other in a hypothetical $MPD - Q_E$ "phase space", despite the wide range of physics and engineering assumptions invoked to characterize each of the ARIES designs.

3. For a given design approach to the tokamak power plant, choices not related to plasma physics, but concerned with materials, configuration, and related (inherent or passive) LSA ratings (and reduction in the cost of particular subsystems), strongly impact the definition of an "optimal" design. While advanced fission reactors are projected to achieve LSA = 2, fusion must carefully choose advanced, expensive materials and other design features to attain an LSA = 2 (or better rating).

4. For all (steady-state) ARIES designs considered, current-drive requirements and the need to minimize associated costs in relationship to the cost of other subsystems are major drivers in the design optimization. Long-pulsed tokamak reactors that do not require non-inductive current drive can trade off costs of subsystems uniquely related thereto (*i.e.*, energy storage, added fatigue-related structure, added pulsed energy transfer and storage systems) with reduced plasma heating (current-drive) power and related balance-of-plant (BOP) needs; recent studies of long-pulsed tokamak power plants without the benefits of any externally controlled profile shaping, however, may produce power that is more expensive than any of the DT-fueled ARIES designs.[13]

5. Divertor issues that critically limit next-step tokamak designs[7,8] to varying degrees have also limited the ARIES designs. Recognition of the difficulty of the divertor problem is reflected in the choice of high edge-plasma density (70 % of the volume-averaged density, compared to 33 % for the ITER/CDA[7]). The ARIES-I design invoked a conventional divertor configuration, which required a high plasma radiation fraction ($f_{RAD} > 0.5$) to reduce divertor-plate heat fluxes; a penalty of 10 % in the cost of electricity results. Innovative, but unproven, gaseous divertors in ARIES-II/IV were invoked, with no such adverse impact upon the design or plant economics. Furthermore, both the average and edge-plasma densities are a factor of 2-4 times greater than the Greenwald (average plasma density)[14] and and a factor of 4-8 times the Borass(edge plasma density)[15] density disruption limits. In comparison, the ITER/CDA design held these respective limits to within a factor of 1.25 for the Greenwald limit and a factor of 1.65 for the Borass limit. The applicability of these density limits to plasmas with the kinds of gradients assumed for ARIES, compared to those in devices for which they were derived, remain to be determined, albeit separatrix power densities are similar but the core-plasma confinement is different.

6. Because of resource limitations, a number of crucial issues for the viability and cost of all tokamak power plants considered by ARIES were left unquantified:

   - impact, frequency, and control of plasma disruptions; the divertor-plate coating thickness was sized to deal with ~ 10 disruptions per annum.

   - longevity of divertor and other plasma-facing components both under normal steady-state, normal transient, and unanticipated transient conditions; although the divertor *per se* is not a high cost item, increasing the plasma radiation fraction ($f_{RAD} > 0.5$) needed to reduce divertor heat loads (ARIES-I) results in reduced plasma and FPC mass power densities, which in turn led to significant (10 %) increases in capital costs.

   - reliability, availability, and mean-time-to-failure *versus* mean-time-to-repair; all ARIES designs assumed ~ 75% plant availability, irrespective of TF-coil peak field, peak heat fluxes, structural materials, primary coolant kind and conditions, *etc.*

B. General Lessons

The design-specific lessons derived from ARIES are distilled below into as concise a bottom line as is allowed by the pre-conceptual, scoping nature these studies. This summary collection of lessons is organized largely along the major technical lines.

- Physics: Significant progress has been made in the theoretical and experimental components of tokamak physics, and the ability of that physics base is sufficient for purposes of pointing out optimal directions towards a viable commercial power plant. Simultaneous achievement of conditions needed for a high-Q_E, high-MPD, ES&H-attractive tokamak power plant, however, remains as a crucial experimental goal. For example, while the plasma temperature was optimized with respect to current-drive power *versus* fusion power density, these profiles remain collectively unoptimized or inconsistent with respect to the longevity of the divertor, high-β plasma operation, and/or the need for a highly ($\geq$ 50 %) radiating plasma that remains safe from density-related disruption limits. The ARIES Project, however, has gone farther than any previous tokamak reactor study in quantifying and implementing the interconnectivity between physics and technology. Of particular import was the determination of: a) plasma configurations where bootstrap current can be aligned in direction and magnitude with the main plasma current, thereby significantly minimizing current-drive requirements (*e.g.*, increasing Q_E), and b) "natural" plasma shapes that minimize the energy stored in the poloidal magnetic field; these important conceptual findings will be explored experimentally.[8]

- Engineering: Until the physics comes together in the sense described above, the engineering of blankets and shields will remain focused primarily on achieving high thermal-conversion efficiencies along with safety and environmental excellence, without a strong focus on the needs of an irresistibly attractive (*e.g.*, more compact, higher power density) commercial power plant. For example, if it were determined that blanket power densities (and first-wall neutron loadings) for reasons of economics and operational practicality had to be increased, and the tokamak plasma physics permitted this to happen, a number of blanket/coolant combinations would be eliminated. The divertor engineering, on the other hand, remains largely in the hands of an incomplete physics data base and the reactor interpretation thereof. For the range of β values examined, the superconducting magnets must be capable of producting peak magnetic field at the windings in the range 14-19 T and engineering current densities of 24-39 MA/m^2. Crucial engineering issues related to disruption mitigation and control, fusion-power-core reliability and availability, and realistic assessments of the time and procedures needed to inspect, maintain, and repair the tokamak fusion power core could not be adequately treated within the resources of the ARIES Project.

- Economics: All the ARIES designs would not be competitive with respect to present projections [11,16] for Advanced Light-Water (fission) Reactors. The ARIES designs are uneconomic because; a) they recirculate too much power (*i.e.*, Q_E is too small); and b) the fusion power core is too massive and expensive [*i.e.*, $MPD(kWe/tonne)$ is too small, and the unit costs of key FPC components are too large]; and c) without direct-energy conversion the *net* thermal-conversion or plant efficiency, $\eta_p = (1 - 1/Q_E)\eta_{TH}$, is no better than for conventional fission or fossil power plants. Both Q_E and MPD are controlled largely by tokamak physics. The ARIES designs have minimized the current-drive power and cost; however, generally too much power is recirculated. Even complete elimination of current-drive power and costs is not sufficient to make the ARIES designs economically competitive with present projections of advanced fission power sources, because of the low MPD values. Engineering can effectively deal with much higher blanket power densities, given that power-density peaking can be controlled (*i.e.*, through high-f_{RAD} plasmas), and increased blanket power density will focus blanket options. Divertor heat loads beyond those in the ARIES designs, however, are difficult to envisage; this problem rests within the physics (*i.e.*, use more of the first-wall as a high-heat-flux surface, more radiation from the plasma). In the context of ARIES, COE is an appropriate figure of merit for reactor optimization. Furthermore, COE is a reasonable discriminator of FPC optimization, since the Reactor Plant Equipment accounts for 62-72% of the direct cost ($\sim$ 33 % for fission[16]). Lastly, the ARIES studies have shown that tokamak-based fusion power cannot use enhanced ES&H merits to resolve the economic issue. As emphasized throughout this assesment, these conclusions are based on present cost projections for advanced fission power.

- ES&H: The economic credits envisaged for inherent or passive safety, even if they actually exist, are not sufficient to counteract the high cost of generating electricity with the ARIES tokamaks. This anticipated credit has provided the main reason for the pervasiveness of the SiC/He blanket/shield system in the ARIES Project, despite issues with respect to (large-component) fabricability, reliability, and cost of this advanced material. Even with the ~ 20 times reduction in neutron production enjoyed by ARIES-III(D-^{3}He/HT-9M/OC), it was shown that the wrong choice of materials could make it as "hazardous" as ARIES-I(DT/SiC/He). The ES&H cost credits assumed in ARIES, although large, were not sufficient to counter the high cost of the materials used. Hence, ARIES has shown that the tokamak power plant must be sold on merits other than (solely) ES&H "attractiveness"; the latter is an essential, but not sufficient condition for the introduction of fusion power into the market place. Furthermore, the engineering penalties (*e.g.*, use of advanced materials, reduced power density, *etc.*) of achieving this necessary condition must be better assessed. Lastly, it should be recognized that advocates of advanced fission-power systems are dealing with all ES&H issues, in addition to having a system that both works as an efficient and "economically attractive" electric power generator.

IV. CONCLUSIONS

The ARIES Project has shown that the (relative) economics of a steady-state tokamak power plant improves with minimizing external current drive power; optimizing plasma temperature; advancing magnet and blanket technology; elimination of the expenses associated with nuclear qualification through passive or inherent safety features; and plasma stability control for high-performance plasma configurations, particularly if β can be increased while minimizing total plasma current and maximizing to nearly 100% the self-driven bootstrap current. Achievement of these conditions whereby plasma disruptions, current-drive efficiency, and the longevity of plasma-facing components are all adequately controlled for a plasma with sufficient confinement and impurity control, however, presents a large uncertainty that can be resolved only by experimental devices with increased relevance to reactor conditions of the kind suggested by ARIES. Central to the achievement of a tokamak plasma configuration with increased Q_E, MPD, economic competitiveness, and EH&S merits is a capability for practical, detailed plasma profile control through tailored heating and (to a lesser extent) fueling under conditions that assures divertor longevity.

While ITER is expected to make important contributions to the understanding of long-pulsed, alpha-particle-heated DT plasmas, the ITER design[7] so far is based primarily on a scaling upward in size of known physics (Fig. 1) rather than an exploration in directions where practical tokamak power stations may reside. At a considerably reduced scale, TPX[8] is being designed to demonstrate the feasibility of tokamak physics advances needed for an economically attractive reactor, as indicated by the ARIES Project and described above. Future fusion reactor studies will evaluate the potential of pulsed tokamaks[13], advanced tokamaks, as well as non-tokamak approaches in the continuing search for competitive, environmentally acceptable nuclear fusion power.

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