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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. Summarized herein are the composite conclusions and lessons developed in the course of four conceptual tokamak power-plant designs. A general conclusion from this extensive investigation of the commercial potential of tokamak power plants is the need for combined, symbiotic advances in both physics, engineering, and materials before economic competitiveness with developing advanced energy sources can be realized. Advances in materials are also needed for the exploitation of environmental advantages otherwise inherent in fusion power.

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 team¹ and does not represent an ARIES Projects consensus; this systems assessment, however, benefited from review and critique from most Project members. A focus is placed on the economic, safety, and environmental impacts of key physics, engineering, and operational assumptions that form the bases of the ARIES tokamak power-plant conceptual designs. This focus is implemented primarily through the cost impact of key physics, engineering, and material choices and assumptions. 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 CO₂, reduced mining, eased nuclear licensing, unlimited fuel supply, *etc.*) is well recognized; 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

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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.

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 degree of extrapolation required in either Physics or Engineering, with this necessarily qualitative metric defined as follows:

- **Present-Day:** achievable by a reasonable extrapolation and a modest (5-10 year) period of directed R&D, starting from a firm experience base that may have been developed either within fusion or in an equivalent non-fusion technology.
- **Near-Term:** achievable by a modest extrapolation into partially understood, advanced areas with little or no equivalent experience base.
- **Aggressive:** achievable only by a large extrapolation into unproven areas with no equivalent experience base.

Even though the metric is subjective, this matrix proved useful in defining, guiding, and executing the project. This matrix remains useful for characterizing the ARIES designs. The location of each ARIES design has been evaluated before and after each design study, and the related shifts are indicated in Fig. 1; the reasons for these shifts are discussed in the following section. Also illustrated on Fig. 1 are the R&D trajectories for both ITER⁷ and TPX⁸, with both the Physics and Engineering goals for each being assumed to be achieved through a relatively short R&D period with high confidence.

Fig. 1. Physics-Engineering configurational space used to target goals and objectives for each ARIES design. The phase-space position required to achieve a given ARIES design is indicated for each, with any migration that occurred because of the design process being indicated. Also shown are the ITER⁷ and TPX⁸ experiments presently being designed.

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. The design summaries given in the following section reflect this re-normalization process at the level given in Ref. 1 to assure maximum quantitative benefit from the design intercomparisons given below.

The main goal here is to summarize the composite technical lessons derived from the ARIES Project. Concept-specific lessons are summarized in Ref. 1, and a compilation and comparison of all ARIES designs are given in Ref. 2. While each of the ARIES designs is summarized in the following Sec. II., the final design reports for each⁴⁻⁶ should be consulted for details, with Refs. 1 and 2 also recapitulating modifications and adjustments conducted throughout ARIES to assure a common-basis comparison of all four concepts.

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

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 capacity⁹. The ARIES-I' and -III' designs shown in Fig. 2. include improvements and/or refinements developed and applied after publication,^{4,5} during the ARIES-II/IV study. Table II 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 both short-term releases and longer-term wastes might be reduced.

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. As is shown in Fig. 1, a post-study assessment indicated that indeed the ARIES-I design retained its original goal of "Aggressive" Engineering and Near-Term Physics, but some aspects of the combined physics requirements for ARIES-I could arguably push Physics towards more Aggressive regions (e.g., achieving high

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	V ₅ Cr ₅ Ti	HT-9M	SiC
Tritium breeder	Li ₂ O	Li	-	Li ₂ O
Neutron multiplier	Be	Tlon ^(d)	Fe-1422	Be
Shield	SiC	Tlon ^(d)	Fe-1422	SiC
MAGNETS (Nb ₃ Sn)				
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	7
decommissioning	0	1	1	0
fuel	0	0	18	0

^(a) Detailed parameter listing and comparison in Ref. 1

^(b) FSR = First Stability Regime; SSR = Second Stability Regime.

^(c) OC = organic coolant (mixed terphenyls).

^(d) Tennon (a manganese steel)

^(e) uses advanced, tenary Nb₃Sn.

^(f) $\epsilon = P_c/P_{ET}$, fraction gross electric power recirculated.

^(g) LSA = 1 inherently safe; LSA = 4 needs active safeguards.

bootstrap-current fractions for the plasma density profiles required for adequate divertor longevity).

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 cost-of-electricity, COE(mill/kWeh), with a range of fission and fossil (coal) power stations¹¹ that have been normalized to the same ($P_E = 1,000$ MWe) net-electric capacity and year (1992) to facilitate comparison with similar unit energy cost projected from the ARIES designs. While the IPWR, APWR-MU, and Coal-MU designs minimize the capital-return component of the COE at ~ 28 mill/kWeh, the inherently more massive FPC (*i.e.*, lower mass power density, MPD(kWe/tonne, re: Table I) of fusion requires nearly twice as much capital return. 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. In fusion, the direct costs, which are approximately half of the total costs, 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 D-T fueled ARIES-I' (as well as ARIES-II/IV) the first-wall, blanket, and shield costs because of sheer mass requirements (not only high unit 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-³He and the impact of reduced neutron production in a tokamak fusion reactor. Completed in 1991, the D-³He-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 for the D-³He-fueled system is a fusion power core that operates for

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 life of the plant and does not require periodic replacement.

While an important goal of the ARIES-III study was to show that these advanced fusion fuels can further improve the safety and environmental qualities of fusion power plants, the neutron production from the side reactions occurring in the D-³He 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), conspired to hold 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 remove the accident driving force and to enhance the LSA rating to 1, but the decrease in thermal-conversion

Fig. 3B. Histogram of the Cost-of-Electricity (COE) values projected for both ARIES and a range of fossil and fission power stations¹¹ 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)

efficiency (from 44 % to 35 %) slightly overrode the increased-LSA cost credit to raise the COE by ~ 1 mill/kWh. In addition, the advances in tokamak physics and plasma performance needed to burn these fuels represent major extrapolations from present-day results. After an extensive assessment of FSR tokamak physics, the use of SSR advanced-tokamak physics was invoked, because the FSR projected a COE that is 20% higher than for the SSR. Even with advanced-SSR physics, however, the level of plasma performance required steps that are possibly beyond beyond 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 $B_{\phi c} = 14$ 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). The operational benefits of ^3He as a fuel, however, can be realized only by evoking extraterrestrial sources, since this particular isotope of helium is extremely rare on Earth.

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) plasma performance, that is more advanced than assumed for ARIES-I but is less extrapolative than for ARIES-III. The main benefits of the yet-to-be-achieved second-stability regime, as applied to ARIES-II/IV, are promises of reduced plasma current and increased bootstrap currents rather than for enhanced plasma confinement efficiency. 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 a 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. 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 those 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 cost difference between FSR and SSR, however, is 21 %. 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 should at least give way to consideration of an upgrade to an "Aggressive" Engineering requirement, as is suggested in Fig. 1.

III. KEY FINDINGS

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

presented as much as is possible in qualitative terms; the detailed reports¹⁻⁶ should be consulted for specific details.

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 are 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 fuel costs, can be comparable to fission fuel costs. The cost credits related to reduced nuclear hazard and waste generation were not sufficient to reduce COE for the range of steady-state tokamak power plants studied by ARIES, to values comparable with advanced fission power at a common plant capacity factor (75 %).
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 II]. Both the shape and location of economic optima resulting from this balance to maximize both Q_E and MPD depend sensitively and often unintuitively 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 under 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.¹⁵
5. Divertor issues that critically limit next-step tokamak designs^{7,8} to varying degrees have been bypassed in the ARIES designs. Recognitions 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/CDA⁷) with negligible impact on economics. The ARIES-I design invoked a conventional divertor configuration, which required a high plasma radiation fraction ($f_{RAD} > 0.5$) to reduce the heat flux incident upon the divertor plates; a penalty of 10 % in the cost of electricity results. 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)¹² and a factor of 4-8 times the Borass(edge plasma density)¹³ 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.
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 quantified:
 - impact, frequency, and control of major 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 ($f_{RAD} > 0.5$) to reduce divertor heat loads by increasing plasma temperature, as was assumed for 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 (MTTF) *versus* mean-time-to-repair (MTTR); 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 of these studies. This summary collection of lessons is organized largely along the major technical lines.

- **Physics:** Although significant progress has been made in the theoretical and experimental components of tokamak physics, the ability of that physics base to provide *simultaneously* all that is required of a commercial power plant is insufficient for purposes of pointing out optimal directions towards a viable commercial power plant. 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. The ARIES Project has gone farther than any previous tokamak reactor study in quantifying and implementing the interconnectivity between physics and technology.
- **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 significantly larger, and the tokamak plasma physics permitted this to happen, a goodly number of blanket/coolant combinations would be abandoned. The divertor engineering, on the other hand, remains largely in the hands of an incomplete physics data base and the reactor interpretation thereof. The magnets have a generally clear mandate from reactor studies done to date: the reactor will use as much magnetic field the magnet designer can practically provide, irrespective of the plasma physics for the range of β values examined. 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 maintain and repair the tokamak fusion power core remain largely ignored.
- **Economics:** All the ARIES designs would not be competitive with respect to 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 efficiency can be 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, simply too much power is recirculated. Even completely eliminating all current-drive power and costs is not sufficient to make the ARIES designs economically competitive with advanced fission power sources. 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 distill blanket options and help focus. Divertor heat loads beyond those in the ARIES designs, however, are difficult to envisaged; this problem rests in the hands of 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 fission¹⁴). Lastly, the ARIES studies have shown that tokamak-based fusion power cannot use enhanced ES&H merits to resolve the economic issue.
- **ES&H:** The economic credits envisaged for inherent or passive safety, even if they actually exist, are insufficient to counteract the high cost of generating electricity with the ARIES tokamaks. Still, this single issue has provided the sole 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-³He/HT-9M/OC), it was shown that the wrong choice of materials could make it as "hazardous" as ARIES-I(DT/SiC/He). Hopefully, 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 marketplace.

Furthermore, the engineering penalties of achieving this necessary condition should 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 the plasma confinement efficiency (β) can be increased while minimizing total plasma current and maximizing 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.

While ITER is expected to make important contributions to the understanding of long-pulsed, alpha-particle-heated DT plasmas, the ITER design⁷ 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 TPX⁸ is being designed to illuminate the feasibility of tokamak physics advances needed for an economically attractive reactor, as indicated by the ARIES Project. Future fusion reactor studies will evaluate the potential of pulsed tokamaks¹⁵, advanced tokamaks, as well as non-tokamak approaches in the continuing search for competitive, environmentally acceptable nuclear fusion power.

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