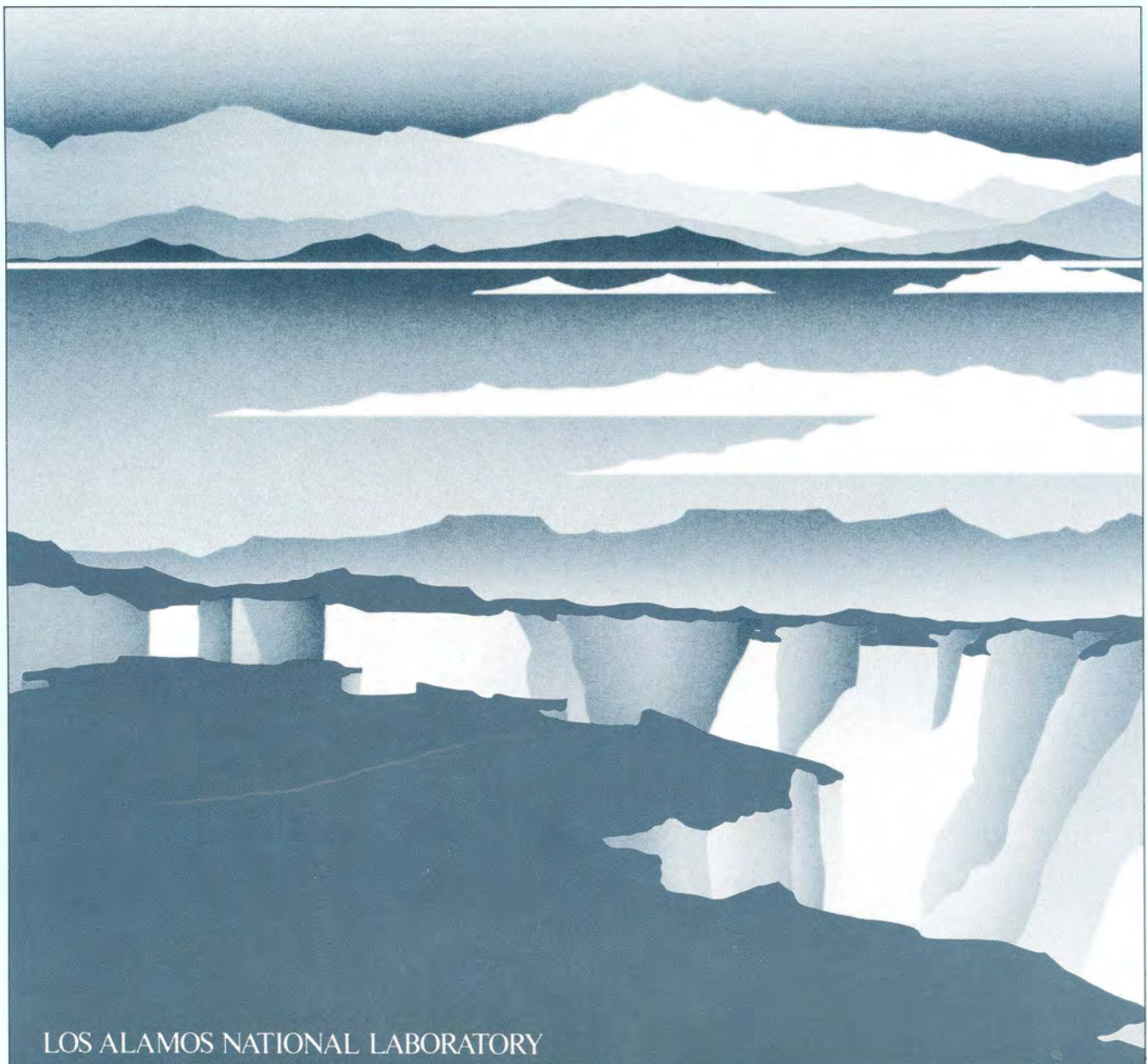


**LESSONS LEARNED FROM THE TOKAMAK ADVANCED
REACTOR INNOVATION AND EVALUATION STUDY (ARIES)**

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LESSONS LEARNED FROM THE TOKAMAK ADVANCED REACTOR INNOVATION AND EVALUATION STUDY (ARIES)[†]

R. A. Krakowski, C. G. Bathke, R. L. Miller, and K. A. Werley

Abstract

Lessons from the four-year ARIES (Advanced Reactor Innovation and Evaluation Study) investigation of four commercial magnetic-fusion-energy (MFE) power-plant embodiments of the tokamak are summarized. These lessons are derived from the physics; engineering and technology; economics; and environmental, safety, and health (ES&H) characteristics of these conceptual tokamak power-plant designs. This summary of ARIES lessons is intended to provide a general indicator of the requirements of economically and environmentally attractive fusion power. The integration of fundamental tokamak physics with conceptual engineering models through a cost-based systems methodology has been especially thorough in ARIES. The resulting quantitative tradeoffs among tokamak plasma physics, plasma engineering, and a wide range of supporting reactor engineering disciplines, and the enhanced interdisciplinary understanding of the impact of constraints leading to optimal tokamak reactors are major contributions of the ARIES Project. A general conclusion drawn from this extensive investigation of the commercial potential of tokamak power plants is the need for combined, symbiotic advances in both physics and engineering before economic competitiveness with developing advanced energy sources can be projected. Comparable advances for materials are also needed for the exploitation of ES&H advantages related to passive safety and reduced radioactive-waste burden. Although the above-mentioned integration of physics, engineering, economics, and ES&H components is an ongoing process limited by present understanding, and although many of the ARIES assumptions remain to be verified experimentally, a preference has emerged for following the path of second-stability-regime tokamak physics towards an optimal (*i.e.*, cost-competitive, operationally tractable, ES&H-acceptable) commercial end-product. The feasibility of this optimal tokamak reactor cannot be assessed, however, until experimental results confirming the necessary physics, engineering, and materials underpinning the ARIES designs become available. Research and Development (R&D) along several independent lines, therefore, would be prudent to assure the necessary advances needed for an economically competitive system with which to harness the nearly unlimited supply of nuclear-fusion fuel in a safe and environmentally benign configuration. While a moderate extrapolation from the existing tokamak data base using presently (or easily) qualified engineering materials will not attain this goal, ARIES has provided a clear indication of the potential reactor merits of the second-stability-regime tokamak plasma with *both* high confinement efficiency (β) and high overall current-drive efficiency (*i.e.*, both low total plasma current and high bootstrap-current fraction); an important related condition is the need for a plasma that sheds a majority of the heating energy through radiation channels so that heat loads on plasma-facing components can be more equally distributed for the more-compact, high-engineering-gain reactor that would result.

[†]Work supported by US DOE, Office of Fusion Energy.

I. INTRODUCTION

A. Approach and Scope

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 focuses 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. The level of quantitative integration of physics and engineering achieved by the ARIES project exceeds that of previous, broad-based studies of tokamak reactors. The interconnectivity of the physics and engineering models and associated results in understanding how best to achieve economically competitive, operationally attractive, safe, and environmentally acceptable reactors has been a main focus in each of the ARIES designs. This summary and assessment of lessons derived from ARIES is independent of the ARIES Project, but has benefited from review and critique from many Project members. The focus of this summary and assessment is primarily on the cost impact of key physics and engineering choices and assumptions. The detailed physics and engineering results from ARIES are deferred to a more technical Project report¹.

The main goal of this report is to compile the technical lessons derived from the ARIES Project and to express the consequences of these technical lessons in a cost-based systems context, within the limitations of the understanding and models used to express that understanding, as elaborated below. Physics and engineering solutions to those issues that limit the overall attractiveness of the tokamak power plant are identified. These limiting issues are expressed generally in terms of the following ARIES bottom-line results: a) the ES&H goals set for ARIES were met only through the use of expensive, unconventional materials; b) the present economic projections for all ARIES designs are 50% or more higher than for other advanced nuclear energy sources; and c) the ES&H cost benefits, as quantified by ARIES, were insufficient to counter the cost impacts of the generally low-power-density, low-to-medium engineering-gain ARIES designs. That ARIES technically advanced the conceptual feasibility of assembling a complex configuration of unconventional materials around the tokamak plasma for purposes of generating net-electric power is well documented in Ref. 1. 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, *etc.*) is well recognized; in a rational world, however, even these attributes must be expressed on a common costing basis for informed choices to be made. Although these as-yet-unquantifiable social, technical, and economic aspects of ARIES are recognized, they were not included as an identifiable task for ARIES, and, hence, are not explicitly treated in this summary assessment. Exclusion of these as-yet-unquantifiable issues from this assessment, however, does not diminish their importance and the cloudiness they contribute to any future projection of form and role for fusion in the overall energy equation.

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; c) to have developed and implemented a safe and economic means for radioactive waste disposal; and d) to have

found a similarly safe and economic solution to the long-term fuel supply problem. These assumptions also largely apply to ARIES. While progress is being made in these areas, complete resolution is not in hand, particularly for countries that enjoy a (short-term) abundance of inexpensive energy, like the U.S. 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, more acceptable waste form, 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 energy in the overall energy picture.

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 reactor might be found.

B. ARIES Background

The ARIES Project was initiated in late 1988², was completed in late 1992³⁻⁵, and was funded by the U.S. Department of Energy, Office of Fusion Energy at a total cost of about \$12 million. The ARIES Project investigated the physics, engineering, economic, and ES&H potential of the tokamak approach to magnetically confined fusion power. The ARIES Project also set as a goal the identification of high-payoff areas of fusion research that could lead to significant improvements in the overall promise of tokamak reactors. The lessons derived from the ARIES Project and summarized herein are used to identify high-leverage areas of fusion R&D. These lessons are expressed largely in terms of cost impacts of physics, engineering, and ES&H choices based on the understanding and models available to ARIES, as discussed in Sec. I.A.; broader, qualitative, and often subjective issues must also be given adequate visibility when assessing the overall outcome of ARIES and the contribution made to the overall fusion R&D planning process.

The ARIES Project was directed by the University of California at Los Angeles, the day-to-day task management was provided by General Atomics, and the overall effort was conducted by a national team with foreign participation. As is indicated on Table I, the ARIES team represented a sufficiently wide spectrum of institutions and expertise to achieve the broadest consensus on solutions to the many complex and interconnected technical issues that arose in the course of the study. With the benefit of regular peer reviews conducted both within the Project and at a wide range

TABLE I. List of Participating Institutions in the ARIES Study

Institution	Area of Responsibility
Argonne National Laboratory	physics, engineering
AEA Culham Laboratory	engineering
California Institute of Technology	physics
General Atomics ^(a)	physics, engineering, materials
Georgia Institute of Technology	physics
Japan Atomic Energy Research Institute	physics, systems, engineering
Kurchatov Institute of Atomic Energy	systems
Idaho National Engineering Laboratory	safety, engineering(safety)
Los Alamos National Laboratory	physics, systems, engineering
Massachusetts Institute of Technology	engineering(magnets)
Oak Ridge National Laboratory	physics, systems, engineering
Princeton Plasma Physics Laboratory	physics
Rensselaer Polytechnic Institute	physics, engineering
TSI Research	engineering(neutronics)
University of California at Berkeley	physics, safety
University of California at Los Angeles ^(b)	physics, engineering, materials
University of Illinois at Urbana-Champaign	physics
University of Wisconsin at Madison	physics, systems, engineering(neutronics), materials

^(a) day-to-day project management

^(b) project responsibility and direction

of fusion-technology and scientific meetings, the ARIES team was able to produce results that reflect a contemporary and normalized view by scientific and engineering communities of the future potential, required R&D, and spectrum of options for the tokamak approach to fusion power¹.

A range of tokamak reactor concepts was considered by the ARIES team in a series of studies identified as ARIES-I, -III, and -II/IV. Each study explored the impact of different sets of assumptions on the degree of extrapolation from the present physics and/or engineering data bases needed to achieve each tokamak power-plant 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 that invoke various 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.² Each design is located in this phase space by the following qualitative measure of the degree of extrapolation required in either Physics or Engineering:

- 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 (*e.g.*, 12-T superconducting magnets).

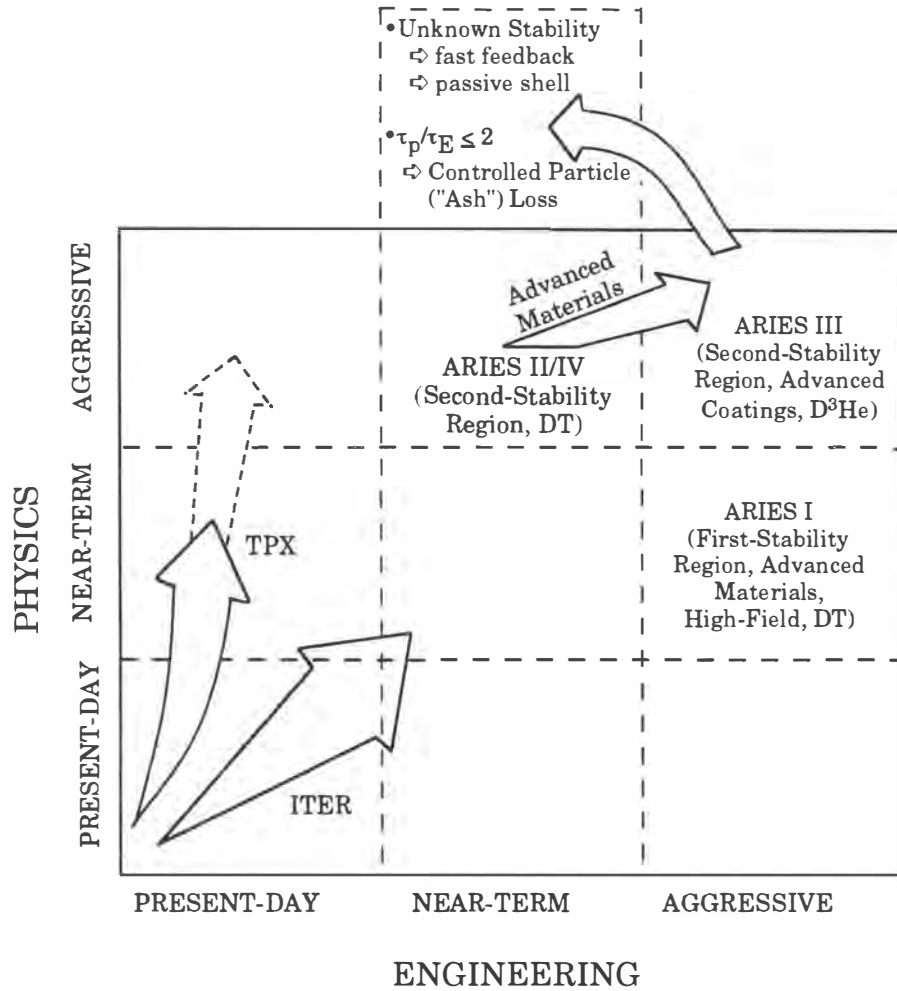


Fig. 1 Physics-Engineering configurational space used to target goals and objectives for each ARIES design. The phase-space position required to achieve each ARIES design is indicated, with any migration that occurred because of the design process being indicated. Also shown are the ITER⁶ and TPX⁷ experiments presently being designed, with ITER advancing the DT ignition/burn components of the tokamak physics data base, and TPX pushing more for commercial reactor relevance in advanced, steady-state tokamak plasmas; both are expected to advance the fusion engineering data base in a number of crucial areas.

- Near-Term: achievable by a modest extrapolation into partially understood, advanced areas with little or no equivalent experience base (*e.g.*, 16-T superconducting magnets).
- Aggressive: achievable only by a large extrapolation into unproven areas with no equivalent experience base. (*e.g.*, > 16-T superconducting magnets).

The Engineering-Physics matrix depicted on Fig. 1 was generated at the beginning of the ARIES Project² to establish the scope and goals of each of the ARIES approaches to tokamak fusion power. Even though the metric is subjective, this matrix proved useful in defining and guiding the project. This matrix also remains useful for characterizing the ARIES designs with respect to *expected* (pre-study) and *actual*

(post-study) extrapolations. 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 ITER⁶ and TPX⁷, with both the Physics and Engineering goals for each assumed to be achieved with high confidence through a relatively short R&D period. The relative positions of TPX and ITER in this configuration space reflect (as a minimum) a moderately successful operation of both, with both devices pushing tokamak physics in different directions: DT ignition/burn for ITER, and reactor-relevant containment efficiency (β), current-drive efficiencies, and divertor environment for the steady-state TPX. Additionally, if a "time metric" could be attached to each coordinate of Fig. 1, that metric could easily reflect a compression along the Physics axis relative to the longer, more-expensive trajectory that generally characterizes developments along the Engineering axis.

All ARIES studies constrained tokamak operation to steady state, thereby necessitating some form of non-inductive (no transformer action) plasma current drive. This constraint was a major driver in establishing the size, physics parameters, and technologies for all ARIES designs; efficient current drive at high plasma confinement efficiency (β) is the single, most-important determinant of reactor technical and economic viability. The studies were periodically updated and normalized throughout the Project by closely coupled, cost-based systems analyses, using the ARIES Systems Code (ASC), 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 in progress. The design summaries given in the following section reflect this re-normalization process so that a maximum quantitative benefit can be derived from the design intercomparisons given below; generally, limitations of time and resource did not allow these ASC-renormalized design points to be followed by detailed conceptual (re-)engineering studies.

The main goal of this report is to compile the technical lessons derived from the ARIES Project and to express the consequences of these technical lessons in a cost-based systems context, within the limitations of the understanding and models used to express that understanding (Sec. I.A.). While each of the ARIES designs is summarized in Sec. II., the final design reports for each³⁻⁻⁵, as well as relevant literature and conference reports, should be consulted for details. Appendix A lists a majority of the ARIES publications generated by the Project over the past five years. In addition, Ref. 1 gives a comprehensive technical summary of the ARIES "lessons learned". Following the design summaries of Sec. II., a listing of key issues and findings for each of the ARIES designs is given in Sec. III. A collection of key lessons is summarized in Sec. IV., which also includes a brief conclusion.

II. DESIGN SUMMARIES

Figure 2 compares the fusion-power-core (FPC) profiles of the four final (ASC-generated) ARIES designs. To give an appreciation of the size of the nuclear-heat-generating element that is the heart of the tokamak power plant, the ARIES FPCs are compared with the comparable system for a Pressurized-Water (fission) Reactor (PWR) of like capacity⁸. The PWR lies near the high end of the compactness spectrum, with the (net-electric) power-to-mass ratio for the system depicted on Fig. 2 being in the range 800-1,000 kWe/tonne; the comparable ratio for the ARIES designs lies in the range 70-110 kWe/tonne, which is ~ 10 times less than for the PWR, but represents a factor of ~ 2 improvement over earlier tokamak reactor projections⁹. Each quadrant in Fig. 2 is "up-down" symmetric and represents a figure-of-revolution about the central axis. Poloidal-field (PF) coils as well as blanket and shield details are omitted to maintain simplicity. The higher-field ARIES-I toroidal-field (TF) coils are thicker because of additional internal structure and the generally lower engineering current density predicted by the TF-coil scaling used. A relatively larger clearance between the plasma and the outboard TF-coil legs is provided in ARIES-II/IV for the horizontal maintenance scheme adopted for those designs [the added TF-coil costs incurred because of this maintenance scheme translated into a $\sim 5\%$ increase in the cost of electricity, COE (mill/kWeh)]. The relatively large plasma cross section for ARIES-III results from the lower fusion power density for D-³He relative to D-T fuel.

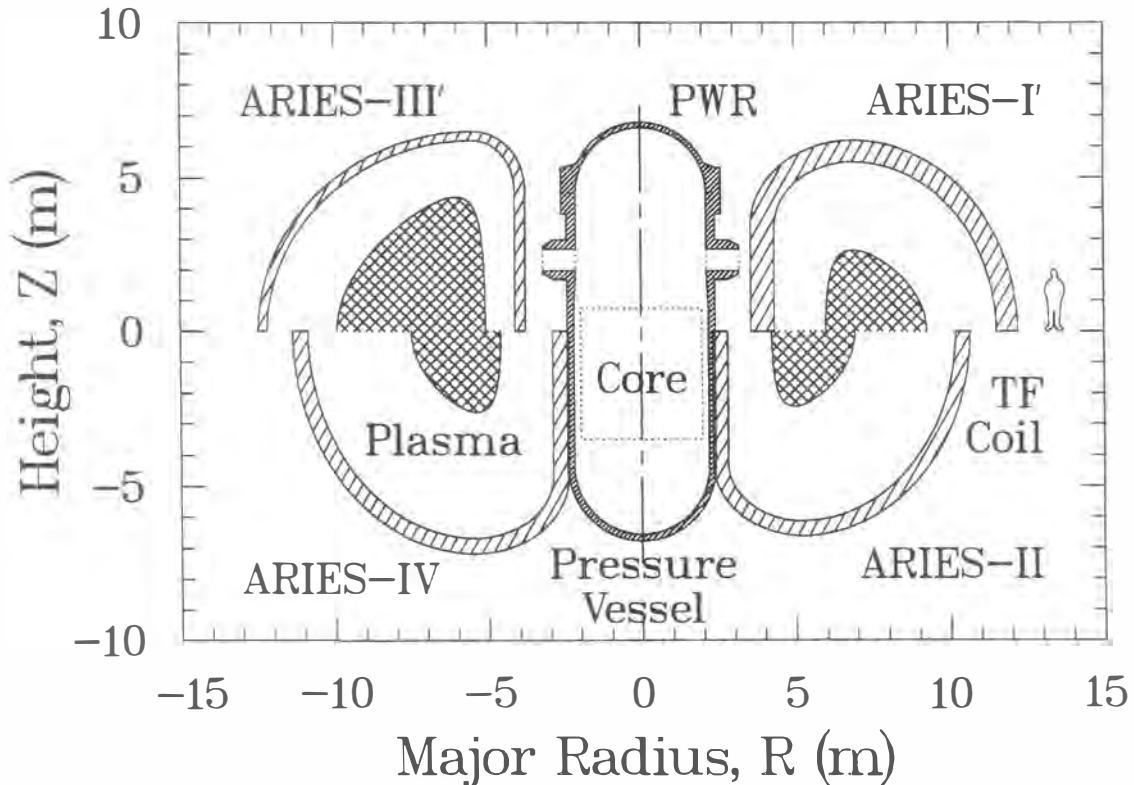


Fig. 2. Fusion-Power-Core (FPC) figure-of-revolution (refer to the centerline, $R = 0$) cross sections for the final 1-GWe ARIES designs. A Pressurized-Water fission Reactor (PWR) of comparable (1.1 GWe) net-electric power is also shown.⁸

The ARIES-I' and -III' designs⁵ shown in Fig. 2 and used elsewhere in this report include improvements and/or refinements developed after publication,^{3,4} and incorporate insights developed during the ARIES-II/IV studies. Although ARIES-I' and ARIES-III' were not subject to conceptual engineering design, the inclusion of these re-optimized ASC updates gives the broadest basis for intercomparison and assessment, despite the potential to inject confusion; while ASC is not a direct substitute for detailed conceptual engineering design of key engineering subsystems, ASC provided strong guidance to the ARIES engineering design and materials activities, as well as being responsive to results generated by these activities (*i.e.*, ASC is a "living" systems-model that reflected new insights and developments occurring throughout the Project in physics and engineering, as well as providing a tool for examining quantitatively the consequences of a wide variety of hypothetical design and physics changes).

Table II summarizes key design features for each of the ARIES designs, along with safety and economic figures-of-merit. The 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, although in some instances the high cost of the unconventional materials needed to achieve the safety-related cost credits produced a strong countering effect. In a generally undifferentiating way, these safety-related cost credits reflect the possibility of removal of nuclear pedigree ("N-stamp") requirements on specific plant components as well as the elimination of safety-related equipment *per se*. The long-term benefits of reduced waste-disposal requirements because of the use of low-activation materials was not reflected directly in the ARIES costing, other than to use a relatively low D&D charge. Appendix B gives a more detailed parameter list for each of the ARIES designs. Detailed isometric, plan, and elevation drawings for each of the ARIES fusion-power-core designs are given in Appendix C. Cost comparisons made between ARIES designs and advanced nuclear fission systems in Table II and Fig. 3 are based primarily on Advanced PWRs, with the fossil-fuel (coal) example including some additional cost incurred for the "clean" use of coal. The fuel-breeding Liquid-Metal (fission) Reactor (LMR) would provide a more meaningful (long-term) comparison for fusion, but recent designs and associated (common-basis) costs for the breeding LMR do not exist; the COE for the non-breeding LMR, however, is comparable to the APWRs (COEs in the mid-40 mill/kWeh range).¹²

The sum of capital and operating costs expressed as a unit cost of product (*i.e.*, COE), along with total cost, is an important measure of competitiveness and attractiveness from the viewpoint of the electric utility (or other operating company of the future). Cost, while important, is not the only figure-of-merit by which the attractiveness of a given design can be measured: reduced complexity, eased operability, maintainability, reliability, licensability, waste generation and disposal, and level of risk both to the public and to the plant investment are also important, but less-quantifiable, measures of plant attractiveness. While fusion generally offers advantages of nearly unlimited fuel supply, zero emissions of greenhouse gases, and reduced mining impact, advances are required before many of these other less-tangible items can be claimed as merits. Furthermore, cost "credits" for reduced nuclear risk and fairly uncertain (unit) costs characterize the COE estimates used in ARIES, with experiences in the fission power industry indicating that estimates of future costs through "appraisal optimism"¹⁵ are underestimated. Hence, while cost has provided

TABLE II. Summary of 1-GWe ARIES Tokamak Power-Plant Designs ^(a)

ARIES	I'	II	III'	IV
FUEL CYCLE	DT	DT	D- ³ He	DT
GEOMETRY				
Plasma major toroidal radius, R_T (m)	7.64	5.60	7.50	6.04
Plasma minor radius, a (m)	1.70	1.40	2.50	1.51
Plasma vertical elongation, κ	1.80	2.03	1.84	2.03
Plasma 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
Average ion temperature, T_i (keV)	20	10	55	10
Electron density, n_e ($10^{20}/\text{m}^3$)	1.26	2.50	3.17	2.90
Confinement multiplier, ¹² H_{IP}	2.7	3.1	7.2	3.1
Radiation fraction, f_{RAD}	0.50	0.18	0.67	0.23
Plasma toroidal current, I_p (MA)	10.9	6.43	29.9	6.64
Bootstrap-current fraction, f_{BC}	0.68	0.87	0.75	0.87
Plasma 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/SiC	V ₅ Cr ₅ Ti	HT-9M	SiC/SiC
Tritium breeder	Li ₂ O	Li	NA	Li ₂ O
Neutron multiplier	Be	—	Fe-1422	Be
Shield	SiC	Tlon ^(d)	Fe-1422	SiC
First-wall/blanket life, $I_w\tau$ (MWyr/m ²)	13. ^(e,f)	16.4 ^(g)	20.	13. ^(f)
MAGNETS				
Conductor	Nb ₃ Sn ^(h)	Nb ₃ Sn	Nb ₃ Sn ^(h)	Nb ₃ Sn
Peak Field at TF coil, $B_{\phi c}$ (T)	19.1	15.9	14.0	15.9
Magnetic-field energy, W_B (GJ)	213	83	169	93
Total specific energy, W_B/M_c (MJ/kg)	42	34	55	34
REACTOR PERFORMANCE				
Thermal conversion efficiency, η_{TH}	0.49	0.46	0.44	0.49
Engineering Q-value ⁽ⁱ⁾ , $Q_E = 1/\epsilon$	4.66	6.49	4.28	5.20
Neutron wall loading, I_w (MW/m ²)	2.06	2.90	0.08	2.67
Average first-wall heat flux, q_w (MW/m ²)	0.42	0.31	1.38	0.32
Mass Power Density ^(j) , MPD (kWe/tonne)	71.7	92.6	88.8	111.0
Level of Safety Assurance, LSA ^(l)	1	2	2	1

TABLE II. (continued)

ARIES	I'	II	III'	IV
COSTS ^(l)				
Unit Total Cost, UTC (\$/We)	4.40	4.17	4.24	3.67
Cost of Electricity, COE (mill/kWeh) ^(m)	101	84	99	90
Cost of Electricity, COE (mill/kWeh) ⁽ⁿ⁾	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 ^(o)	0

(a) Appendix B contains a more detailed listing of ARIES design parameters.

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

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

(d) Tenelon (a manganese steel)

(e) ARIES-I, as reported in Ref. 3, used 20 MW/m²

(f) based on a nominal 3% burnup of SiC

(g) based on 200 dpa in vanadium alloy

(h) uses advanced, ternary Nb₃Sn superconductor.

(i) $\epsilon = P_c/P_{ET}$, fraction of gross electric power returned to tokamak power plant.

(j) ratio of net electric power, P_E , to mass of fusion power core (FPC, mass of the plasma chamber, blanket, shield, magnets, primary coolant manifolds, and associated structure).

(k) based on a scale of 1-4, with LSA = 1 being inherently safe and LSA = 4 requiring active engineered safeguards¹⁰.

(l) All costs are in "constant" 1992 dollars.

(m) COE projected without LSA cost credits (LSA = 4).

(n) COE projected with cost credits appropriate for designated LSA rating; cost components indicated.

(o) based on 1.15 M\$/kg for lunar ³He¹¹.

the main object function for understanding and selecting optimal ARIES designs, and its use is continued in this assessment, the import of the above-mentioned less-quantifiable figures-of-merit should not be overlooked. Finally, as elaborated in Sec. I.A., economic comparisons with advanced nuclear fission systems are based on the assumption of a positive resolution of issues (for fission) related to public acceptance, time of licensing, the safety and economics of waste disposition, and the economic closure of the nuclear fuel cycle; these issues for ARIES have been resolved either by design or assumption.

A. ARIES-I/ARIES-I'

The ARIES-I design was completed in 1990 and is a Deuterium-Tritium(DT)-fueled reactor that would rely on modest improvements from present-day physics results based on the first-stability regime (FSR) of plasma performance. Ion-cyclotron fast-wave current drive was used in conjunction with high-field ternary Nb₃Sn magnets, low-activation SiC composite-material structure, and helium cooling of a blanket based on Li₂ZrO₃ tritium breeder that required a beryllium neutron multiplier. The technologies for ARIES-I are significantly more advanced than those available today (Fig. 1). These technologies are assumed to be achievable in about 20 to 30 years, if adequate development programs are initiated and/or enhanced, particularly in the areas of advanced, low-activation materials; efficient and economic radiofrequency power systems; and advanced high-field superconducting magnets. In choosing design features for ARIES-I, those that would maximize the environmental and safety attributes were given the strongest emphasis, as was the case for all ARIES designs. Post-study assessment indicated (Fig. 1) 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 Aggressive regions (*e.g.*, achieving high bootstrap-current fractions with the plasma density profiles accurately controlled to assure MHD stability, minimum disruptivity, high radiation fractions, and the edge-plasma conditions required to assure divertor longevity).

Since each completed ARIES design was re-analyzed with the evolving ASC in the course of the subsequent ARIES design to assure that a self-consistent intercomparison emerged at the end of the Project, the ARIES-I design was subjected to the greatest evolution over the course of the ARIES Project. The ARIES-I' design⁵ summarized in Table II and Appendix B has been updated from the original ARIES-I design³ in accordance with the evolving groundrules and model updates that occurred throughout the Project. This "update" is based on a re-analysis using ASC and could not be subject to a detailed conceptual engineering (re-)design. The ARIES-I blanket was adopted for ARIES-IV and improved (*i.e.*, costs reduced) during the course of the ARIES-IV study. The ARIES-I' design incorporates the improved ARIES-IV blanket. Summarized below is the ARIES-I \Rightarrow ARIES-I' design evolution.

- ARIES-I: the updated version includes: correcting all costs for inflation,⁵ the introduction of a safety rating (LSA = 2),¹³ updating of material and magnet costs,^{5,13} refinement of indirect-to-direct cost algorithm,^{5,13} small dimensional changes to meet better resolved shielding requirements,¹³ a reduction in the SiC radiation life from 20 to 13 MWyr/m², and the incorporation of an improved model with which to compute plasma power balance.⁴ The cost of electricity with these changes is 101 mill/kWeh in 1992 \$.

- ARIES-I': the updated version (Table I) includes a more realistic TF-coil scaling for engineering current density *versus* peak field (24.5 *versus* 25.9 MA/m² for ARIES-I) and the use of the ARIES-IV blanket (212 *versus* 312 \$/kg and LSA = 1 *versus* 2 for ARIES-I, respectively), but still using the ARIES-I blanket maintenance scheme (*i.e.*, closer-fitting TF coils). In 1992 \$, the COE is 77 mill/kWeh [a 9 % increase in COE relative to ARIES-I for more realistic (lower engineering current density for same conductor field, higher unit cost) TF coils, a 21 % decrease for lower unit blanket costs, and a 12 % decrease for a more favorable ($2 \Rightarrow 1$) LSA rating].

These COEs compare to 65 mills/kWeh (75 mills/kWeh in 1992 \$) originally reported in Ref. 3. Again, most of these ARIES-I adjustments reflect the application of lessons derived from the ARIES-IV study to the ARIES-I design as the former evolved.

The ARIES-I(FSR) and ARIES-IV(SSR) designs also provide an opportunity for a self-consistent comparison between tokamak reactors based on first- and second-stability-region plasmas. A series (ARIES-Ia - ARIES-Ic) of ASC designs were constructed that systematically isolated engineering differences between ARIES-I and ARIES-IV on the basis of cost. Summarized below is a systematic description of the differences between ARIES-I and ARIES-IV performed expressly for a comparison of first- *versus* second-stability plasmas; this material is presented only as an inter-comparison and is not an ARIES-I update.

- ARIES-Ia: replace the 21-T TF coils with the 16-T ARIES-IV TF coils (24.9 *versus* 25.9 MA/m² for ARIES-I and 92.7 *versus* 97.8 \$/kg for ARIES-I) \Rightarrow the minor plasma radius a increased from 1.55 to 1.97 m, and the COE increased from 101 (updated ARIES-I, as described above) to 110 mill/kWeh for $A = 4.5$. Although not tracked in this series of modifications, the optimal COE occurs at lower plasma aspect ratio¹³ under the assumption of lower-field TF coils.
- ARIES-Ib: exchange ARIES-I (Li₂ZrO₃ breeder) blanket for safer (LSA = 1 *versus* 2 for ARIES-I), less-expensive (212 *versus* 312 \$/kg), thinner (1.33-m *versus* 1.39-m for the inboard and 1.76-m *versus* 1.79-m for the outboard) ARIES-IV (Li₂O) blanket; includes extra (1.5-m) TF-coil standoff for horizontal maintenance and thinner scrapeoff (50 *versus* 100 mm). \Rightarrow COE decreased from 110 to 92 mill/kWeh.
- ARIES-Ic: a gaseous divertor (ARIES-II/IV) is used in place of a high-recycle divertor. This change removes the constraint that required plasma radiation fraction $f_{RAD} \geq 0.5$ and had set the average plasma temperature at 20 keV; the temperature re-optimizes at 12 keV, leading to increased plasma fusion-power density. \Rightarrow COE decreased from 92 to 84 mill/kWeh.

The bottom line for a comparison of FSR(ARIES-Ic) *versus* SSR(ARIES-IV) tokamak reactors using the same blanket and TF-coil designs is 84 *versus* 68 mill/kWeh (a 19 % reduction) instead of the 77 *versus* 68 mill/kWeh (a 12 % reduction) indicated on Table II that includes differences in blanket and TF-coil designs. Re-optimization of the plasma aspect ratio, as indicated above, would have decreased these COE differences somewhat. The evolution described above is a good example of the application of the ASC ability to perform common-basis comparisons and to separate the physics and engineering cost drivers.

B. ARIES-III

The ARIES-III design was initiated out of numerical sequence with the ARIES-II/IV second-stability-region (SSR) designs to allow an early assessment of the D-³He fuel cycle 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 in exchange for a significant reduction in neutron production (by a factor of ~ 20) and subsequent radioactivity generation in structural materials. Furthermore, the reduced neutron environment makes possible a simpler shield (a tritium-breeding blanket *per se* is not required) that is designed only to recover heat and to protect the magnets, while using materials (ferritic steel) and coolants (low-pressure, high-temperature organic fluids) generally not applicable, from an activation and waste-generation viewpoint, for use in the intense neutron fluxes associated with DT-fueled systems. An important goal for the D-³He-fueled system is a fusion power core that operates for the life of the plant and does not require periodic changeout; while this goal may be achieved on average from the viewpoint of neutron-induced radiation damage, major plasma disruptions may intervene unpredictably to reduce this lifetime goal. Table II and Appendix B give key parameters, and Fig. 3 compares direct and unit costs projected for ARIES-III.

While an important goal of the ARIES-III study was to show that this advanced fusion fuel 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 ferritic (HT-9M) alloy used and, along with the chemical energy stored in the low-pressure organic coolant (OC), combined to hold the safety rating to that of the DT-fueled ARIES-I design (LSA = 2). A cursory re-analysis at the systems level (*i.e.*, no engineering design *per se* was performed) of ARIES-III indicated that if the organic coolant could be exchanged for pressurized water to remove the accident driving force, the LSA rating could be enhanced to 1, but the decrease in thermal-conversion efficiency (from 44 % to 35 %) slightly overcompensated the increased-LSA cost credit to raise the COE by ~ 1 mill/kWeh. Whether a pressurized-water-cooled blanket could in fact be substituted for the OC base case is questionable because of the high heat fluxes and the thin walls that originally led to the choice of high-temperature (*i.e.*, high thermal efficiency, η_{TH}), low-pressure organic coolant.

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 results in a COE that is 20% higher than the already expensive SSR case. Even with advanced-SSR physics, however, the level of plasma performance required steps that are possibly beyond the "Aggressive" categorization, as is suggested on Fig. 1, because: the Troyon coefficient is 2.5 times that of ARIES-II/IV; τ_p/τ_E is 2-5 times less than for other ARIES designs; and active feedback stabilization of kink MHD modes is required. The final (cost) optimization of the SSR ARIES-III indicated 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). Although ARIES-III might be considered as "Near-Term" Engineering because of the use of

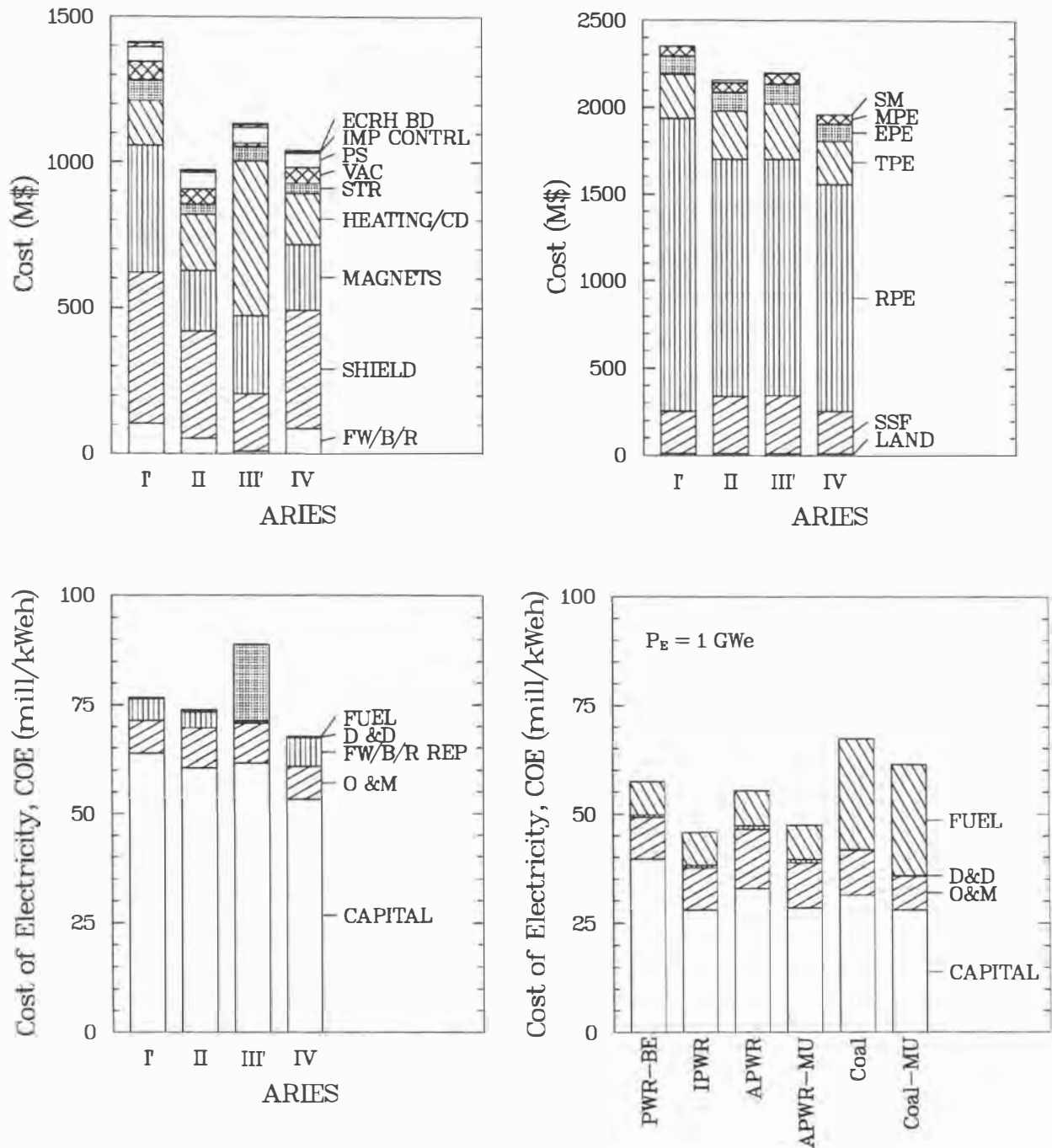


Fig. 3. Histogram of direct costs for key Fusion-Power-Core (FPC) components and main power plant subsystems for all ARIES (final, normalized) designs. Shown also are the Cost-of-Electricity (COE) values projected both for ARIES and for a range of fossil and fissile power stations¹⁴ of comparable capacity ($P_E = 0.6$ -1.2 GWe, scaled to $P_E = 1,000$ MWe assuming $COE \sim 1/P_E^{0.6}$) in Constant-1992 Dollars. Cost projections for non-breeding LMRs indicate COEs that are comparable to the APWR (mid-40 mill/kWh range).¹² Refer to Nomenclature for definition of terms used in this figure.

low-pressure OC and ferritic-steel structure, a composite (double-layer) Be/W-coated high-heat-flux first wall (W is needed to inhibit chemical interactions between the beryllium coating and the ferritic-steel substrate) that must be designed to survive major plasma disruptions provides an argument for keeping the Engineering rating in the "Agressive" category. The operational benefits of ^3He as a fuel, however, can be realized only by evoking extraterrestrial sources, since this particular isotope of helium is rare on Earth. This helium isotope could also be bred through the $\text{Li} \rightarrow \text{T} \rightarrow ^3\text{He}$ cycle, but the radioactivity problem being addressed by the $\text{D}-^3\text{He}$ cycle would be concentrated in the satellite tritium generator, which, in addition to storing large inventories of tritium, would also be a significant power generator.

C. ARIES-II/IV

The ARIES-II and -IV studies were conducted concurrently, with both being completed in late 1992. The second-stability-regime plasma operated with low total current and a high bootstrap-current fraction; active current drive is provided by a mix of lower-hybrid and ion-cyclotron fast waves. These DT-fueled reactors invoke the same plasma performance that is more advanced than that assumed for ARIES-I, but less extrapolative than required for ARIES-III. Specifically, while all ARIES designs are stable to $n = \infty$ toroidal MHD ballooning modes, only ARIES-I was shown to be stable to the low- n kink modes; ARIES II/IV was found to be unstable to the $n = 1$ kink, unless a conducting structure is located a radial distance < 1.25 times the plasma radius and the plasma is rotating, but ARIES-II/IV is stable to the $n > 1$ kink mode. The stability of the ARIES-III design is similar to that of the ARIES-II/IV, except the stability of the $n > 1$ kink is not known, and helical feedback coils are invoked to stabilize the other low- n modes, but the conducting shell required for stability to the $n = 1$ kink can be located as far out as 1.6 times the plasma minor radius. In addition, the ARIES-II/IV plasma performance is less extrapolative in energy confinement, but equally extrapolative in the required particle times (but for different reasons) than is required for ARIES-III because of the higher τ_p/τ_E ratio (9-10 *versus* 2, respectively). The main benefits of the yet-to-be-achieved (other than as a local transient or for uninterestingly low β values) second stability regime, as exploited in ARIES-II/IV, are associated with reduced plasma current and increased bootstrap currents rather than for enhanced plasma confinement efficiency (β).

The ARIES-II study used a blanket system based on an insulator-coated (TiN, to reduce MHD pressure losses in the liquid-metal coolant) 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 also requires a beryllium neutron multiplier. As described in Sec. II.A., 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 % (Sec. II.A.). 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, even with LSA credits). 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

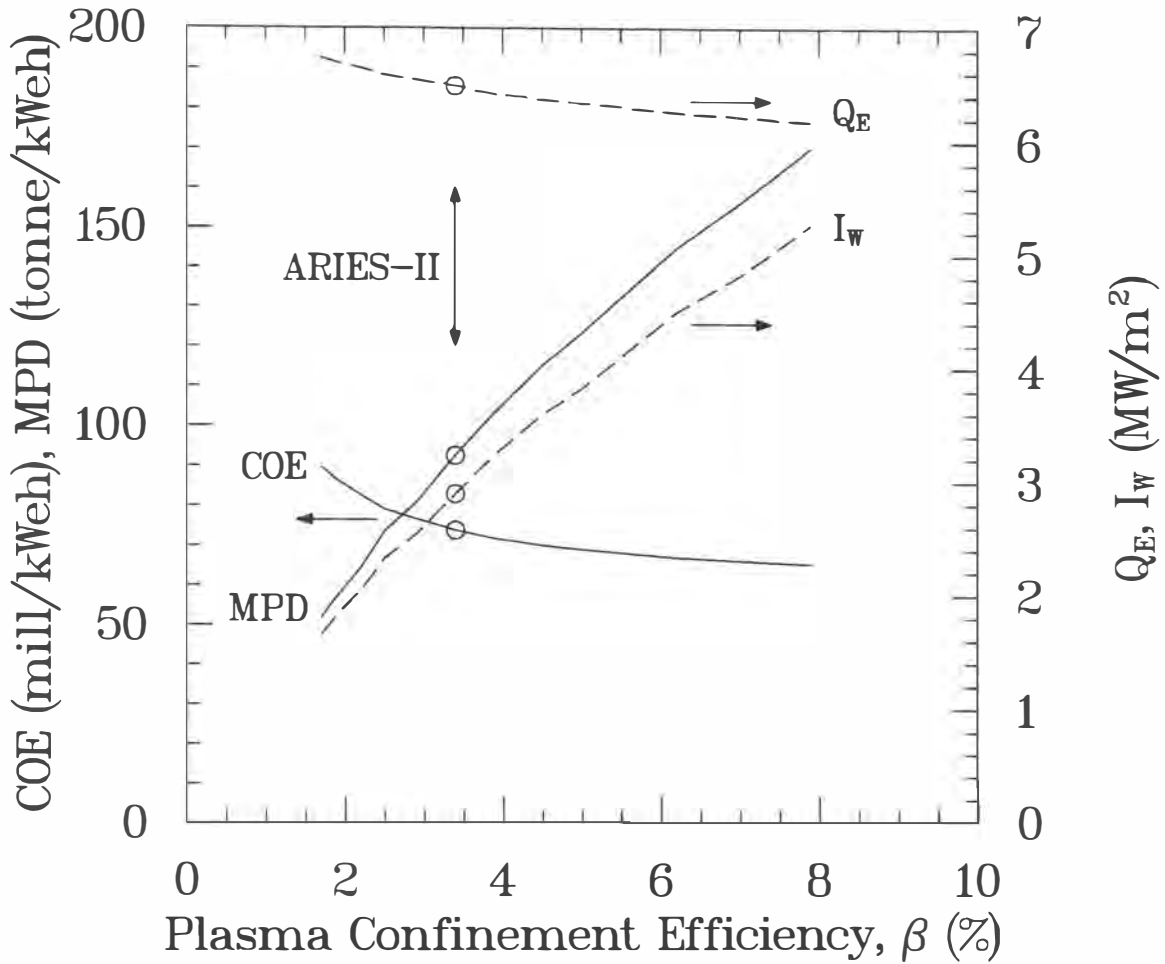


Fig. 4. Sensitivity of the cost of electricity, COE, for the ARIES-II design⁵ to variation in the plasma confinement efficiency, β . Also shown are the mass power density, MPD; the engineering gain, Q_E ; and average neutron wall loading, I_w ; versus β . These results are based solely on ASC parametric studies, using ARIES-II physics and engineering assumptions, with no conceptual engineering design study of these higher-power-density blankets.

difference between FSR and SSR, however, is 19 % relative to FSR (23 % relative to SSR). 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.

A recurrent theme throughout the ARIES designs is the need to maximize the engineering gain, Q_E , with this ratio of gross-electric power to total recirculating power determined largely by both the level and the overall efficiency of current drive. Equally important is the need to maximize MPD by increasing neutron wall loading, I_w (MW/m²), and blanket power density primarily by maximizing β . Generally, the (cost) optimal tokamak reactor represents a (physics and engineering) constrained balance that maximizes both Q_E and MPD to an extent allowed by physics and engineering limitations. The second-stability ARIES-II/IV designs were expected

to maximize both Q_E and MPD, but the MHD stability for the profile used for the plasma "safety-factor", q , limited β to 3.4 %. Although the bootstrap-current fraction, f_{BC} , for the q profiles used is high, the current-drive efficiency was lowered by the need to cancel bootstrap overdrive currents in the edge-plasma region with inefficient lower-hybrid current drive. Other stable q profiles may offer higher β with increased current-drive efficiency, but an examination of the MHD stability of such profiles could not be completed within the scope of the ARIES Project. The benefits of higher β , as well as related engineering concerns (*i.e.*, neutron and thermal wall loadings, as well as related blanket power densities), are illustrated in Fig. 4 for the ARIES-II design;⁵ the high overall current-drive efficiency characterizing that design was used. The ARIES-II was used for this ASC "design" because the Li/V blanket can best accommodate the higher power densities that accompany these higher-MPD systems, although it is emphasized that a conceptual engineering design remains to be made. Along with the reduced COE at higher β is an increased neutron wall loading, which may focus the blanket options on high-power-density, liquid-metal blankets of the kind used in ARIES-II. Typically, higher heat fluxes to the divertor are associated with the higher I_w values, making high- f_{RAD} plasmas and the divertor even greater issues for higher- β , higher-MPD tokamak reactors. Also of concern for the higher β cases reported in Fig. 4 is the reduction in Q_E ; this reduction results from the increased plasma density needed to maintain constant net-electric power generated from a reduced plasma volume (*i.e.*, $P_{CD} = n_e I_p R T (1 - f_{BC}) / \gamma$). The improvement in COE with increased β diminishes at $\beta > 5$ % because the two major cost components affected by β , magnets and shield, are reduced to minor roles in determining the total cost at high β , with the diminished Q_E as β increases in part causing the COE decrease to saturate. This asymptotic decrease of COE (Fig. 4) with increasing β leads to improved, but still uncompetitive, values for ARIES-II. The asymptotic value of COE, however, is dependent upon design detail (*e.g.*, q profile or blanket materials) and has the possibility of being lower. Future supporting physics studies that search for higher- β second-stability plasmas must also continue the optimization of overall current-drive efficiency, and Q_E , through further increases in f_{BC} , decreases in current overdrive, or both.

D. Comparisons with Alternatives

The direct costs of major power-plant accounts, the direct costs of key FPC subaccounts, and the COE components are shown for ARIES in Fig. 3, which also includes a COE comparison with a range of fission and fossil (coal) power stations.¹⁴ Costs for the latter have been normalized to the same ($P_E = 1,000$ MWe) net-electric capacity, using a $COE \sim 1/P_E^{0.6}$ scaling and common year (1992) to facilitate comparison with similar unit energy cost projected from the ARIES designs. A consistent long-term comparison of ARIES in principle should be made with other long-term energy sources, such as the breeding Liquid-Metal (fission) Reactor (LMR), but a contemporary breeding-LMR design with common-basis costs is not available to provide a meaningful comparison. Designs for non-breeding LMRs, however, project COEs that are close to those being suggested for APWRs (*i.e.*, in the mid-40 mill/kWeh range)¹². While the IPWR, APWR-MU, and Coal-MU (refer to Nomenclature) designs minimize the capital-return component of the COE at ~ 28 mill/kWeh, the inherently lower MPD for the ARIES designs requires nearly twice as much capital return. The higher capital costs for the ARIES designs cannot be offset by the reduction in fuel

costs expected in proceeding from fossil to fission to fusion. However, the first-wall, blanket, and reflector replacement costs can be comparable to the fuel costs for fission. The lunar- ^3He fuel used in the ARIES-III' design is comparable to the coal fuel cost (with about the same energy resource). 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 (Fig. 3), 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 designs (ARIES-I', -II, and -IV), the first-wall, blanket, and shield costs, because of sheer requirement of mass (not only high unit costs), comprise 43-47 % of the FPC costs; the ARIES-III' neutral-beam current-drive system represents 47 % of the D- ^3He ARIES-III' FPC costs.

These economic (COE) intercomparisons of ARIES concepts with advanced nuclear fission assume that fission has successfully addressed the problems of (mainly U.S.) public acceptance, licensing barriers, waste management, and fuel-cycle costs (Sec. I.A.); shortfalls in accomplishing any one of these goals will amplify and/or extend the ES&H credits used directly (*i.e.*, LSA credits) or indirectly (*i.e.*, 6-yr construction, moderate D&D charges) by the ARIES formalism. If, on the other hand, fission power successfully negotiates these hurdles, a more symbiotic role for fusion may have to be considered.

III. SYNOPSIS OF KEY FINDINGS AND LESSONS LEARNED

The findings and lessons from the ARIES Project are presented here for each of the ARIES designs. These findings and the lessons they project are presented as much as is possible in quantitative terms using COE as the main object function for the reasons discussed and with the caveats given in Sec. I.A.; the references listed in Appendix A. should be consulted for quantitative detail. A comprehensive discussion of technical lessons derived from ARIES, as viewed by the Project, is deferred to Ref. 1.

A. General Findings and Lessons

1. Relative to fissile- or fossil-fuel electrical power generators, fusion systems based on the tokamaks considered by ARIES have higher recirculating powers, convert heat to net electricity with the same efficiency as present-day fissile and fossil power plants, but are generally more massive and rely more on higher technology; the net result for tokamak fusion is higher capital costs. 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 for fusion, although the cost of the full fuel cycle for the former is uncertain. The cost credits related to reduced nuclear hazard, as measured by LSA, were not sufficient to reduce the product costs (COE) for the range of steady-state tokamak power plants studied by ARIES to values comparable to advanced fission power at a common plant capacity factor (75 %).
2. A cost-driven balance forces compromise between engineering gain ($Q_E = 1/\epsilon$, determined primarily by current-drive power) and capital cost of the fusion power core [FPC, *i.e.*, mass of plasma chamber, blanket, shield, magnets, and associated structure, indirectly measured by ratio of net-electric power, $P_E(MWe)$, to FPC mass, $M_{FPC}(tonne)$, or the mass power density, $MPD(kWe/tonne) = 1000P_E/M_{FPC}$].
3. Both the shape and location of economic optima (*e.g.*, point of minimum COE, constrained or not) 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 ARIES designs illustrate the impact of these constraints in generating the variability of the economic balance between Q_E and MPD. Generally, the optimal (*i.e.*, minimum, but not necessarily competitive COE) tokamaks emerging from the ARIES project are too expensive to compete on the same basis (Sec. I.A.) with other advanced energy sources. Although large uncertainties characterize the COEs projected by ARIES, it is unlikely that the COEs are overestimated based on the unit costs, recirculated-power efficiencies, component-replacement costs, and plant availabilities used, which together lead to the general and historically proven tendency for "appraisal optimism" when projecting new and advanced technologies¹⁵.
4. The variability associated with the economic balance between Q_E and MPD, as dictated by both physics and engineering considerations, leads to a range of tradeoffs and possible approaches to the quest for an economically and environmentally acceptable fusion reactor; although presently such a design has not been demonstrated by ARIES, not all options and possibilities were explored. Specifically, the consideration given to the second-stability-regime

plasma strongly indicates a productive direction for future exploration – both high bootstrap current *and* high plasma β , along with low total plasma current (in conjunction with high f_{BC} to increase Q_E) and high radiation fractions (to reduce divertor heat loads in more compact FPCs).

5. 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) safety ratings (LSA and related cost reductions for particular subsystems), strongly impact the characteristics of the optimal (*e.g.*, engineering/physics-constrained minimum-cost) design. Safety-related cost reductions for both fission and fusion result from reduced or eliminated systems, in addition to the removal of "N-stamp" requirements imposed on selected equipment. While advanced fission reactors are projected¹⁶ to achieve LSA = 2, ARIES chose advanced, expensive materials and other complex design features to attain an LSA = 2 or better rating, while relying on related cost credits to narrow the gap between economic competitiveness. If the problems and issues presently deterring wide-spread implementation of advanced energy sources (Sec. I.A.) are not favorably resolved, however, these cost credits as measured by ARIES may be underestimated. Attractive ES&H characteristics, in any event, are a necessary, but not sufficient, condition for the implementation of fusion power, as is the case of fission power.
6. At the onset of ARIES the general goal was to find tokamak physics and engineering configurations that projected both competitive cost *and* attractive ES&H features. The latter goal, in fact, drove all ARIES designs at the expense of the former; ARIES paid the price of unconventional materials to achieve good LSA ratings and a less-than-compensatory cost credit related thereto. If the tokamak physics to which ARIES was constrained allowed higher-power-density systems, ES&H considerations may have limited MPD because of nuclear afterheat concerns, although this concern is also dependent on material choice and configuration. Early in the Project (ARIES-I), a "credibility" issue played an important role in limiting the maximum magnetic field at the TF coil, with the enforcement of this subjective constraint on subsequent ARIES designs also being accompanied by cost penalties. To a large extent, the enforcement of low β limits represented another "credibility" constraint with serious economic impact on ARIES. It would be profitable for the fusion engineering and physics communities to push back; these "credibility" constraints so that significantly improved tokamak power plants can result. The *ad hoc* physics "extension" using the ARIES-II design at higher β values and the associated ASC parametric results given in Fig. 4 indicates a fruitful direction for future work in this regard.
7. 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.
8. Unlike TPX⁷ and ITER⁶, which continue the search for an acceptable solution to the divertor problem, ARIES had to assume that solutions to this difficult problem will eventually be found. All ARIES designs have recognized the divertor

problem by choosing as input high edge-plasma density (45-70 % of the volume-averaged density, compared to 33 % for the ITER/CDA⁶) with negligible impact on economics. The ARIES-I design invoked a high-recycle divertor configuration, which required a high plasma radiation fraction ($f_{RAD} > 0.5$) to reduce the heat flux incident upon the divertor plates, at a penalty of a 10 % increase in the cost of electricity. The use of unproven gaseous divertors in ARIES-II/IV (high-recycle divertors are also unproven) had no such adverse impact upon the design or economics. Furthermore, both the average and edge-plasma densities are a factor of 2-4 times greater than the Greenwald (average plasma density)¹⁷ and a factor of 4-8 times the Borass (edge-plasma density)¹⁸ disruption limits, despite the assumption that all ARIES designs would be nearly free of plasma disruptions (~ 10 per year). In comparison, the ITER/CDA⁶ 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, albeit, the ITER design is conservative in this regard.

9. Systematic, cost-based feedback to earlier ARIES designs generated in the course of advancing newer designs is important; the ability to update completed designs using both commonly evolving computational tools and design personnel is essential to achieving a useful, inter-comparable ensemble of commercial reactor designs.
10. The commonality of analysis tools and the bridge they form between physics and engineering *vis à vis* the cost-based, physics-rooted, engineering-constrained systems-studies task and ASC is vital to the communication with and common assessment of all major components of the ARIES project. This commonality allowed quantitative comparisons to be made of widely differing concepts, as well as the assessment of impact from areas with widely differing disciplines operating under varying techno-scientific priorities and degrees of optimism.
11. Because of a shortage of time and knowledge, a number of crucial issues for the viability and cost of all tokamak reactors remains to be considered.
 - impact, frequency, and control or mitigation of major plasma disruptions; the divertor-plate coating thickness was sized to deal with ~ 10 disruptions per year.
 - 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 capital-cost item, increasing the plasma radiation fraction ($f_{RAD} > 0.5$) to reduce divertor heat loads by increasing plasma temperature, as was done 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-fail (MTTF) *versus* mean-time-to-repair (MTTR); all ARIES designs and associated cost projections assumed 75% plant availability, irrespective of TF-coil peak field, peak heat fluxes, primary coolant kind and conditions, *etc.*; issues and tradeoffs related to high MPD and neutron-wall-loading designs *versus* very low power density, life-of-plant FPCs, and increased plant availability deserve further exploration and resolution.

B. ARIES-I

1. The conventional approach to steady-state tokamak operation in the FSR (First-Stability-Region) is to invoke low plasma aspect ratio and high plasma current to achieve high Troyon beta values, $\beta = C_T I_p / aB$, and moderate (conventionally achievable through moderate technology extrapolation) TF-coil magnetic fields for fixed Troyon coefficient, C_T . The high plasma current and low bootstrap current, however, lead to high current-drive power, $P_{CD} = n_e I_p R_T (1 - f_{BC}) / \gamma_i$ and a low engineering gain, $Q_E = 1/\epsilon$. The increased costs of both current-drive power systems and the added BOP required to provide the higher recirculating power fraction, ϵ , are appreciable and drive the design cost optimization to higher A and lower β , provided higher-field coils are available.
2. Reducing recirculating power by reducing the driven plasma current, $I_p(1 - f_{BC})$, by increasing f_{BC} and reducing I_p through increased plasma aspect ratio, A, at the expense of reduced $\beta \sim I_p / aB$ and increased B and TF-coil field (if available) required to maintain high plasma fusion power density, $P_F / V_p \sim (\beta B^2)^2$, represents an economically wise choice. These design choices, however, lead to increased FPC mass and reduced MPD, both because of increased A and decreased TF-coil current density caused by increased coil field, $B_{\phi c}$, [despite increased A, i.e., $B \sim B_{\phi c}(1 - A^*/A)$, where A^* is the plasma/TF-coil standoff distance normalized to plasma radius]. Another reason for the high magnetic field and associated coil cost is the high cost of the blanket and the tendency to reduce the blanket volume through increased magnetic field, to the extent allowed by this balance between two expensive subsystems. In principle, a cost optimum results from this Q_E versus MPD tradeoff, but other physics, engineering, and economic factors can shift or reduce this optimum. In ARIES-I, the importance of this tradeoff is reduced by the aforementioned high blanket unit cost and the resulting shift of the optimum towards systems with higher magnetic fields.
3. The above-described tradeoffs lead to an aspect ratio that optimizes COE; any optimum is strongly dependent on the unit costs of TF-coil (\$/kg), current drive (\$/W for the current-drive *per se*, \$/We or \$/Wt for added BOP, blanket unit costs), and the Troyon coefficient, $C_T \sim \beta B a / I_p$ (the higher this coefficient, the lower is the optimum aspect ratio). The TF-coil mass and total cost, in turn, depend strongly on peak coil fields and current density, as reflected in the highly integrated scaling algorithms used in ASC through a stress-dependent relationship between $B_{\phi c}$ and the coil engineering current density, j_c (MA/m²).
4. Other design choices and scaling relationships strongly impact the economic balance between Q_E and MPD, thereby determining both position and magnitude of cost optima:
 - plasma (particle and current densities) profile control to optimize f_{BC} while assuring minimum impact of fusion power density (a small effect, albeit, the fusion power density is strongly dependent on the average plasma temperature), edge-plasma conditions (high edge density desired to control heat fluxes and protect plasma-facing components), plasma confinement (τ_E), and MHD stability margins (particularly critical for the second-stability-region ARIES-II, -III, and -IV designs).
 - nuclear, safety, and coil-protection parameters of the blanket and shield systems that separate the plasma from the coil system.

5. While the original classification of "Aggressive" Engineering because both high-field TF-coils based on ternary Nb₃Sn superconductor and advanced SiC/SiC-composite blanket structure were pursued remains unaltered, the level of required physics ($f_{BC} = 0.68$ in an $A = 4.5$ system with density profiles controlled precisely to achieve the design value of bootstrap-current fraction, as well as the need to protect the divertor and assure stable plasma operation) may stretch somewhat the classification of ARIES-I as requiring "Near-Term" Physics (Fig. 1).

C. ARIES-II/IV

1. The significant amount of bootstrap current ($f_{BC} = 0.87$) needed to assure that current-drive was not a significant cost driver in this SSR plasma was achieved at relatively low β ($= 0.034$), but cost-optimized designs nevertheless resulted for relatively low MPD (albeit, the highest of all ARIES designs), medium- $B_{\phi c}$ (16 T) systems. That is, the increase in Q_E for the cases examined was obtained at low MPD, and the cost benefits of high- Q_E operation were largely countered by the cost of the massive, high-unit-cost FPC. Hence, although the impediment of current-drive-power intensiveness to increased compactness and power density was reduced in the ARIES-II/IV design, additional restrictions of (cost-imposed) peak field at the TF coil, efficient use of the space at the torus center for TF coils, and (ultimately) neutron-wall-loading limits inhibit increased compactness and power density. This TF-field constraint is imposed through the high unit cost of the TF coils and the rapid decrease in engineering current density (*i.e.*, increased coil size) as $B_{\phi c}$ is increased. Releasing the 16-T coil-field limit lead to a minimum-cost (by ~ 1 mill/kWeh) re-optimization at a coil field of 17 T – β for ARIES-II/IV is the true impediment to FPC compactness, significant increases in MPD, and significant reductions in COE for these higher- Q_E systems. In some ways, however, the lessons from ARIES-I with regard to current-drive power (*i.e.*, minimize I_p and maximize f_{BC} at almost any penalty in reduced MPD) may have been over emphasized for ARIES-II/IV in that exploration of the cost impact of somewhat lower f_{BC} and higher β by the stability analyses may have led to improved SSR designs; this tradeoff falls in the category of "a lesson to be learned." In any event, while increases in both Q_E and MPD for ARIES-II/IV resulted, MHD-stability and f_{BC} constraints as applied gave insufficient economic relief. The ASC parametric results summarized in Fig. 4 indicate a promising direction for ARIES-II if a means can be found to justify more optimistic second-stability-region β values while maintaining (actually increasing somewhat) high overall current-drive efficiency through increased f_{BC} , decreased I_p , and reduced bootstrap-current overdrive.
2. A credible divertor solution was not found, and the future development of one was assumed. The difficult problem of design self-consistency that includes the strong impact of the divertor, longevity of plasma-facing components, and the purity of the plasma were circumvented by the assumption that the gaseous divertor will function adequately; this assumption was made in addition to invoking high ratios of edge-plasma to average plasma densities, but these ratios were not as high as in ARIES-I. The gaseous divertor is untested and represents an "Aggressive" extrapolation of divertor physics.

3. The economic interplay between material choices and LSA cost credits was clearly illustrated. For the same LSA = 4 rating the Li/V ARIES-II design was more economically competitive than the SiC/SiC/He ARIES-IV design (COE = 84 *versus* 90 mill/kWeh), but this ordering was reversed when the ARIES-IV design was awarded a greater safety margin (LSA = 1) because of the greater potential for radioactivity release that could be driven by lithium fires in the ARIES-II design (LSA = 2), leading to COE = 74 *versus* 68 mill/kWeh, respectively, for ARIES-II and -IV.
4. The SSR ARIES-II/IV designs to date represent the best projection of the ARIES tokamak reactors. The significant improvements in physics justify the original Physics classification as "Aggressive" (*i.e.*, the combined need for significant plasma profile control, high bootstrap currents, low plasma currents, good energy confinement, gaseous divertors). The COEs given on the same basis, however, are projected to be 42% higher than advanced-fission systems; parity solely on an economic basis may not be possible for tokamak-based fusion power plants examined by ARIES because of inherent low Q_E and MPD, albeit Q_E for ARIES-II was the highest of all ARIES designs (Table II).
5. With the use of advanced blanket materials, particularly for the SiC/SiC ARIES IV case, question arises as to whether the Engineering should be upgraded from "Near-Term" to "Aggressive" (Fig. 1).
6. If future studies of SSR tokamak plasmas show both high β and high f_{BC} as possible as a means to increase both Q_E and MPD, the resulting higher-wall-loading, higher- f_{RAD} system may favor the V/Li blanket over the SiC/SiC/Li₂O/He system, because of limits on neutron wall loadings related primarily to local blanket power densities (particularly in ceramic breeding materials); Fig. 4 indicates both the economic promise and the engineering challenge of this approach to higher-MPD tokamak fusion power that must find ways to maintain, if not increase, the already high Q_E values.

D. ARIES-III

1. Optimization of the D-³He SSR tokamak suggests TF-coil fields that are significantly lower than anticipated from projections of earlier FSR-tokamak D-³He reactor studies because of the higher β for SSR plasmas. This lower-field system, coupled with the less-than-"Aggressive" HT-9M fusion power core using organic coolant without the need to breed tritium, warrants a down grading of the Engineering from "Aggressive" to "Near-Term". A countervailing force in this regard is the need of a Be/W-coated, high-heat-flux ferritic first wall. The choice of HT-9M alloy, however, led to reductions in the radioactive inventory relative to a DT-fueled system by only a factor of four, even though the neutron production was reduced by a factor of ~ 20 . The down grading of Engineering requirement would be accompanied by an erosion of the safety advantages of the D-³He fuel cycle, with this erosion being aided by the use of organic coolant and the (chemical) energy reservoir it presents for release of radioactive structure in event of a fire. An improved LSA rating would result if pressurized-water could replace the organic coolant, although engineering for the high heat fluxes (*i.e.*, thin walls) in a pressurized system may prove to be difficult. If these engineering difficulties could be overcome, the safety-related reduction in COE remains slightly smaller than the increase in COE caused by reduced thermal-conversion efficiency for

pressurized-water-cooled systems; little or no net economic benefit would result, given that the pressurized-water system could be engineered.

2. The SSR tokamak plasma at $\beta = 0.23$ that is required by ARIES-III is MHD unstable to $n = 1$ kink modes (stability to $n > 1$ is unknown) and would require a passive shell and helical coils located close to the plasma (< 1.6 times plasma minor radius) to perform a fast-feedback function; this function could not be quantified within the limitations imposed by the ARIES Project. Secondly, high confinement enhancement of ~ 7 times present L-mode scaling predictions (ITER-89P¹⁹) is required. Thirdly, the Troyon coefficient required for ARIES-III is 2.6 times that for the SSR plasmas suggested for ARIES-II/IV. Furthermore, the need for a plasma with a particle confinement time that is equal to or less than twice the convective/conductive energy transport time renders a third physics area that is difficult to quantify; the main concern in this regard is the timely removal of fusion "ash", with selective ash pumping being recognized as possibly being needed but not explored by ARIES. Generally, the "Aggressive" ranking suggested for Physics (Fig. 1) may need further upgrading to a more lofty category until these stability and confinement issues can be quantitatively resolved.
3. The burning of D-³He in an FSR-tokamak reactor would require a Physics ranking that is less lofty than that suggested above for the SSR ARIES-III design: the FSR/SSR Troyon coefficients are 0.035/0.151; the ratios of particle-to-energy confinement times are 1/2; and the confinement-time enhancement factors are 4/7, respectively. Since in physics a FSR plasma for D-³He tokamak would push only one out of three parameters (*i.e.*, τ_p/τ_E), compared to all three for the SSR ARIES-III, the Physics for the former is regarded as "Aggressive", whereas that for ARIES-III may be pushed beyond the "Aggressive" ranking (Fig. 1). The requirement for high-field TF coils forces the D-³He FSR-tokamak approach to retain its "Aggressive" Engineering ranking. Even then, the COE projected for the FSR-tokamak D-³He burner would be $> 20\%$ that of the already expensive (COE = 89 mill/kWeh, or ~ 2 times advanced fission) ARIES-III' design; this high cost must be compensated by the reduced radioactive waste and materials damage expected of this approach.
4. Although the possibility for a life-of-plant fusion power core exists for ARIES-III, limitations of the systems model (*e.g.*, constant plant availability, no direct measure of or penalty for total life-cycle radioactive waste volume generation, generally long radiation lifetimes assumed for most blanket/shield materials exposed to DT neutrons) did not allow credits to be awarded for this possibility; model refinements and extensions are needed in this regard, with related implications going beyond the burning of D-³He (*e.g.*, tradeoffs related to neutron wall loading and MPD *versus* increased availability and reduced life-cycle radioactive waste volume).
5. The ³He fuel charge is a relatively important cost driver (20%) and uncertainties in the cost of lunar recovery (1.15 M\$/kg) could swing COEs significantly.
6. Better ways to burn D-³He than in a tokamak may exist and should be pursued²⁰.

IV. SUMMARY AND CONCLUSIONS

A. Summary of Lessons Learned

The design-specific lessons together with key findings in Sec. III. are combined below into as concise a "bottom line" as is allowed by the pre-conceptual nature of ARIES. This summary of lessons is organized along the major technical lines that characterized the four-year ARIES Project.

- **Physics:** Although great 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 reactor at present is not adequate for purposes of identifying a competitive commercial power plant. The utility of optimizing the plasma temperature with respect to current-drive power *versus* fusion power density for profiles that are 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 is questioned. The ARIES Project has gone farther than any previous tokamak study in this regard, but more must be done, much of which will be determined by how wisely the next major tokamak devices^{6,7} are designed, built, and operated. Specifically, the implications of a significantly enhanced current-drive efficiency on the tokamak reactor operating space are great; it is the general conservatism adopted by ARIES in this area, compared to earlier tokamak reactor studies, that directly (*e.g.*, Q_E) or indirectly (*e.g.*, increased A and/or decreased β , leading to decreased MPD) limited the attractiveness of all ARIES designs. The direction for improved tokamak reactors has been indicated by ARIES through a more aggressive implementation of second-stability-regime physics that allows both high- β and high bootstrap-current fractions, while simultaneously operating with low total current, high radiation fractions, and high neutron wall loadings.
- **Engineering:** Until the physics comes together in the sense described above, the engineering of blankets and shields will drift primarily in pursuit of safety and environmental excellence, without a strong focus on attractive reactor economics. 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 than the values adopted by the ARIES designs, and the tokamak plasma physics permitted this to happen, a number of blanket/coolant combinations would be eliminated. On the other hand, if economics of high-availability, low-MPD, life-of-plant FPCs were adequately demonstrated, a broader range of blanket/shield options would emerge. The engineering of the divertor, on the other hand, is being dictated primarily by an incomplete physics data base and the reactor interpretation based thereon. High- f_{RAD} , high-edge-density plasmas would emphasize more the particle-handling rather than the power-handling role of the divertor. The magnets have a generally clear mandate from reactor studies done to date; those studies indicate that the reactor will use as much magnetic field as the magnet designer can practically provide, irrespective of the plasma physics for the (low) range of β values examined, as long as these fields can be generated in conductors with sufficiently high engineering current density and sufficiently low unit costs. For the magnet scalings and unit costs used in ARIES, the magnets combine with the need to minimize expensive

blanket volume while assuring adequate engineering gain, as dictated by current-drive power requirements, to give relatively high optimum costs; increased β at high Q_E in combination with higher performing magnets and reduced unit costs for both magnets and blankets is suggested as a recipe for significant reductions in the COEs reported from ARIES; a rough indication of the economic benefits (at the ASC systems level) promised by this approach is given in Fig. 4. Finally, crucial engineering issues related to disruption mitigation and control, FPC reliability and availability, and realistic assessments of the time and procedures needed to maintain and repair the tokamak FPC were beyond the resources and scope of ARIES and for a good reason: key design drivers in these crucial areas remain captives of an incomplete physics data base that limited the ability of the engineer to project anything more definite, despite the importance of these issues; this observation applies with even greater force if the high-MPD, high- Q_E approach to economically attractive tokamak power plants is pursued.

- Economics: All the ARIES designs are not economically 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 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 is no better than for present-day fission or fossil power plants, despite the need to invoke significantly advanced power-conversion cycles (*i.e.*, high η_{TH}). 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 in ARIES-I and ARIES-III, with Q_E being increased somewhat for ARIES-II/IV. Even the complete elimination of all current-drive power and costs would not be sufficient to make the ARIES-II/IV designs economically competitive with advanced fission power sources unless β and MPD could be increased. Engineering can effectively deal with much higher blanket power densities, and increased blanket power density will distill blanket options and help focus blanket engineering. Divertor heat loads beyond those in the ARIES designs, however, cannot be 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 fission²¹). Lastly, the ARIES studies have shown conclusively that tokamak-based fusion power cannot use enhanced ES&H merits to make an end run around the economic issue. In short: a) materials with enhanced ES&H characteristics are unconventional and expensive; and b) LSA "credits" in fact may not exist, since the safety-related "N-Stamp" and the added cost it represents more than likely will be replaced by a "C-Stamp" (C = Capital) at the request of those wishing to protect the increased plant investment being projected by all ARIES designs, and the revenues that must be generated. These conclusions that ES&H merits are a necessary, but not (economically) sufficient, condition for an attractive fusion reactor relative to advanced nuclear fission is predicated on the assumption that fission power favorably resolves public-perception, licensing, waste, and fuel-cycle issues, at least to the extent assumed by ARIES.

- ES&H: The economic credits envisaged for inherent or passive safety, even if they actually exist (*i.e.*, "N-stamp" *versus* "C-stamp"), 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, neutron-fluence lifetime, 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 also dealing with all three of the letters in ES&H, in addition to having a system that works as an efficient, reliable, and "economically attractive" electric power generator; if fission is successful in this regard, the role of fusion may shift from one of competitor to one of symbiont.

B. 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 (N-stamping) 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, overall current-drive efficiency, and the longevity of plasma-facing components are controlled adequately for a plasma with sufficient confinement and impurity control, however, presents a large uncertainty that can be dispelled only by ambitious and flexible experimental devices like TPX⁷ that are designed and operated with increased relevance to optimal reactor conditions of the kind suggested by the ARIES study. However, even when these economic improvements are fully applied as presently envisaged, the projected cost of generating electrical power from a tokamak reactor will be higher than that for future (advanced) fission power plants; these higher costs, therefore, argue for continued innovative research and must be balanced against the potential for fusion to exhibit improved safety and environmental characteristics compared to fission. For example, through correct configurational and materials choices, disposal of radioactive wastes from fusion reactors should be possible through shallow land burial rather than deep geological disposal. Additionally, fusion reactors may achieve operational levels of safety not obtainable in present fission reactors. Consequently, fusion may be able to close the nuclear fuel cycle sooner than fission in a system with greater perceived public safety. Whether this single merit is sufficient to overcome the expense projected for tokamak-based fusion power, particularly in view of progress being made by fission-power advocates in this regard, remains an important open issue.

Large uncertainties cloud these prognoses, and additional experiments on large, reactor-relevant devices are necessary, as are studies of other tokamak and

non-tokamak confinement systems. While ITER is expected to make important contributions to the understanding of long-pulsed, alpha-particle-heated DT plasmas, the ITER design⁶ so far is based primarily on a scaling upward in size of known physics rather than an exploration in directions where practical tokamak power stations may reside. At a considerably reduced scale, TPX⁷ is being designed to illuminate the feasibility of tokamak physics advances needed for an economically attractive reactor, as identified by the ARIES Project. Future fusion reactor studies will evaluate the potential of long-pulsed tokamaks, advanced tokamaks, as well as non-tokamak approaches in the continuing search for competitive, environmentally acceptable fusion power. In this regard, the following areas deserve more exploration for an economically competitive, operationally practical, and environmentally attractive power plant:

- explore tokamak physics that allow simultaneous attainment of high bootstrap currents ($f_{BC} \sim 0.8-0.9$) and high β (≥ 0.10), along with reduced plasma currents and high radiation fractions ($f_{RAD} \geq 0.6-0.7$).
- with the increased Q_E and plasma fusion power density that would result from the above item, explore the physics of higher plasma radiation fraction ($f_{RAD} \geq 0.6-0.7$) and the engineering of first walls and blankets that can deal with the higher neutron wall loading (*i.e.*, higher local power densities in the first-wall and blanket) and deliver FPCs with higher MPDs in a configuration that maintains the advantages (and necessity) of passive safety.
- explore optimal tokamak reactor configurations that rely primarily on inductive current drive, and compare with ARIES.
- re-invigorate detailed studies of concepts other than tokamaks that allow more flexibility in achieving fusion power plants with both higher Q_E and MPD, while possibly offering higher efficiencies of fusion-power conversion to useful energy forms.
- continue advancing and refining the cost-based systems approach and the interconnectivity between physics, engineering, and ES&H issues it provides.
 - while COE remains the broadest communicative figure-of-merit for the level of studies being considered, use of COE without understanding the public, political, regulatory, ES&H, and supply/demand environment can be misleading; more must be done in quantifying these other issues into a broader-based figure-of-merit and to elevate the related arguments for fusion out of the realm of opinion.
 - continue elimination of the non-uniformity of the systems code models and performance algorithms, particularly with respect to: a) calibrations with ongoing large projects like ITER⁶ and TPX⁷; and b) level/uniformity of system-by-system optimism in unit costs and/or hoped-for breakthroughs (*i.e.*, radiofrequency power, advanced materials, superconducting magnets, *etc.*); relative levels of optimism allowed for physics *versus* engineering.
 - better understanding of the broader implications of figures-of-merit, benefit-to-cost ratios, high MPD *versus* life-of-plant components and the realities of increased plant availability related thereto.

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NOMENCLATURE

Symbol	Definition
A	Plasma aspect ratio, R_T/a
A^*	Normalized TF-coil standoff
a (m)	Plasma minor radius in midplane
ALWR	Advanced Light Water Reactor
APWR	Advanced Pressurized Water Reactor
APWR-MU	Advanced Pressurized Water Reactor, Multiple Units
ARIES	Advanced Reactor Innovations and Innovations Study
ASC	ARIES Systems Code
B (T)	Toroidal magnetic field at plasma
$B_{\phi c}$ (T)	Toroidal magnetic field at TF coil
B_p (T)	Average poloidal magnetic field at plasma edge
BOP	Balance of Plant
C_T (Tm/MA)	Troyon coefficient, $\beta B a / I_p$
CD	Current Drive
CDA	Conceptual Design Activity (ITER, <i>ca.</i> 1988-1992) ⁶
Coal	Coal power plant
Coal-MU	Coal power plant, Multiple Units
COE (mill/kWeh)	Cost of Electricity
D&D	Decontamination and Decommission (charges)
ECRH	Electron Cyclotron Resonance Heating
ECRH BD	ECRH BreakDown system
EPE	Electric Plant Equipment
ES&H	Environmental, Safety, and Health
ES	Energy Storage
f_{BC}	Bootstrap current fraction
f_{RAD}	Plasma radiation fraction
FPC	Fusion Power Core
FSR	First Stability Region
FW/B/R	First Wall, Blanket, and Reflector
FW/B/R REP	FW/B/R REplacement
HEATING/CD	supplemental-heating and CD systems
H_{IP}	ITER-P energy confinement time enhancement factor ¹⁹
IMP CONTRL	impurity control system
IPWR	Improved Pressurized Water Reactor
I_p (MA)	Plasma current
ITER	International Thermonuclear Experimental Reactor
LAND	LAND and land rights
LMR	Liquid-Metal (fission) Reactor
LSA	Level of Safety Assurance
M_c (kg)	Coil mass
M_{FPC} (kg)	FPC mass
MFE	Magnetic Fusion Energy
MPE	Miscellaneous Plant Equipment
MPD (kWe/tonne)	FPC Mass Power Density, P_E/M_{FPC}

NOMENCLATURE (continued)

Symbol	Definition
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NA	Not Applicable
n_e (1/m ³)	Average plasma electron density
O&M	Operation and Maintenance
OC	Organic Coolant
P_c (MW)	Recirculating power (current-drive plus BOP auxiliaries)
P_{CD} (MW)	Current-drive power
P_E (MW)	Net-electric power
P_{ET} (MW)	Total electric power
P_F (MW)	Fusion power
PF	Poloidal Field (coil)
STR	primary STRucture and support
PWR-BE	Pressurized Water Reactor, Best Experience
PS	Power Supply, switching, and energy storage
P_{TH} (MW)	Thermal power
PWR	Pressurized Water Reactor
q	tokamak plasma safety factor, $\sim BA/B_p$
Q_E	Engineering Q-value or gain, P_{ET}/P_c
Q_p	Plasma Q-value or gain, P_F/P_{CD}
R_T (m)	Major plasma toroidal radius
R&D	Research and Development
RPE	Reactor Plant Equipment
SM	Special Materials
SSF	structures and site facilities
SSR	Second Stability Region
TF	Toroidal field (coil)
TPX	Tokamak Physics eXperiment
TPE	Turbine Plant Equipment
US DOE	United States Department of Energy
UTC (\$/We)	Unit Total Cost
VAC	reactor VACuum systems
V_p (m ³)	Plasma volume, $\sim 2\pi^2\kappa Aa^3$
W_B (MJ)	Magnetic energy stored in FPC
β	Ratio of plasma to magnetic pressure
ϵ	Recirculating power fraction, $1/Q_E$
γ (A/W/m ²)	Current-drive efficiency, $n_e I_p (1 - f_{BC}) R_T / P_{CD}$
κ	Plasma elongation
η_{TH}	Thermal conversion efficiency
η_p	Net plant efficiency, $\eta_{TH}(1 - \epsilon)$

APPENDIX A: ARIES Publications[†]

General and Systems Studies:

- G01. F. Najmabadi and R. W. Conn, "The ARIES Tokamak Fusion Reactor Study," IEEE Symp. on Fus. Eng., 2, 1021 (October 2-6, 1989).
- G02. R. L. Miller, "The ARIES-I High-Field-Tokamak Reactor Study: Design-Point Determination and Parametric Studies," Proc 13th IEEE Symp. on Fus. Eng., 2, 1027 (October 2-6, 1989).
- G03. F. Najmabadi, R. W. Conn, and The ARIES Team, "The ARIES-I Tokamak Reactor Study," Fus. Technol., 19(3), 783 (May 1991).
- G04. R. L. Miller and R. A. Krakowski, "Options and Optimizations for Tokamak Reactors: ARIES," Fus. Technol., 19(3), 802 (May 1991).
- G05. J. D. Delene, "Updated Comparison of Economics of Fusion Reactors with Advanced Fission Reactors," Fus. Technol., 19(3), 807 (May 1991).
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[†] G = general and systems; P = physics and plasma engineering; E = engineering and materials; S = safety and environment

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APPENDIX B: Detailed ARIES Design Parameters

TABLE B1. Summary of ARIES Physics Parameters

ARIES	I'	II	III'	IV
Stability regime ^(b)	FSR	SSR	SSR	SSR
Fuel mix, $\phi_D/\phi_T/\phi_{3He}$	50:50:0	50:50:0	50:0:50	50:50:0
Major toroidal radius, R_T (m)	7.64	5.60	7.5	6.04
Plasma minor radius, a (m)	1.70	1.40	2.50	1.51
Plasma vertical elongation, κ	1.80	2.03	1.84	2.03
Plasma triangularity, δ	0.70	0.67	0.81	0.67
Plasma aspect ratio, $A = R_T/a$	4.5	4.0	3.0	4.0
Plasma-edge safety factor, q	4.5	12.2	6.9	12.2
Profile factors:				
peak-to-average density, n_0/n	1.30	1.12	1.06	1.12
peak-to-average temperature, T_0/T	1.90	2.65	1.75	2.65
normalized edge density, n_E/n	0.70	0.45	0.60	0.45
Troyon coefficient, C_T (Tm/MA)	0.032	0.059	0.151	0.059
Plasma beta, β	0.019	0.034	0.24	0.034
Plasma poloidal beta, β_θ	2.80	5.40	5.41	5.40
Stability parameter, $\epsilon\beta_\theta$	0.62	1.35	1.80	1.35
Ion temperature, T_i (keV)	20.0	10.0	55.0	10.0
Electron temperature, T_e (keV)	19.0	10.3	53.3	10.3
Ion density, n_i ($10^{20}/\text{m}^3$)	1.07	2.15	2.01	1.97
Electron density, n_e ($10^{20}/\text{m}^3$)	1.26	2.50	3.17	2.90
Particle-to-energy confinement time ratio, τ_p/τ_E	4	9.8	2	9.15
Ion-to-electron energy confinement time ratio, τ_{Ei}/τ_{Ee}	1	1	1	1
Lawson parameter, $n_i\tau_E$ ($10^{20}\text{s}/\text{m}^3$)	3.11	2.71	22.0	2.90
Confinement multiplier over ITER-89P scaling, ¹² H_{IP}	2.69	3.07	7.18	3.15
Plasma gain, $Q_p = P_F/P_{CD}$	17.8	28.9	16.3	29.8
On-axis toroidal field, $B_{\phi 0}$ (T)	10.6	7.97	7.59	7.63
Radiation fraction, f_{RAD}	0.50	0.18	0.67	0.23
Plasma current, I_p (MA)	10.9	6.43	29.9	6.64
Bootstrap-current fraction, f_{BC}	0.68	0.87	0.75	0.87
Current-drive power to plasma, P_{CD} (MW)	115	66.1	163.2	68.0

TABLE B2. Summary of ARIES Engineering Parameters

ARIES	I'	II	III'	IV
Plasma gain, $Q_p = P_F/P_{CD}$	17.8	28.9	16.3	29.8
Engineering gain, Q_E	4.66	6.49	4.28	5.20
Field at TF coil, $B_{\phi c}$ (T)	19.1	15.9	14.0	15.9
TF-coil stress (GPa)	1.24	0.63	1.36	0.57
TF-coil current density (MA/m ²)	24.5	31.6	39.4	30.0
Magnetic-field energy, W_B (GJ)	213	83	169	93
Total specific energy, W_B/M_c (MJ/kg)	42	34	55	34
Current-drive efficiency:				
γ (10 ¹⁹ A/W m ²)	2.92	1.83	10.9	1.81
I_p/P_{CD} (mA/W)	30.3	13.1	45.9	13.1
Masses (ktonne):				
First wall	0.50	0.43	0.13	0.41
Shield	4.63	6.02	6.33	3.62
TF coils	4.18	1.81	1.93	2.13
PF coils	0.93	0.59	1.15	0.61
Fusion power core	13.9	10.8	11.2	9.01
Fusion power, P_F (GW)	2.04	1.91	2.66	2.02
Neutron power, P_N (GW)	1.63	1.53	0.10	1.62
Neutron wall loading, I_w (MW/m ²):				
14.1-MeV	2.06	2.90	0.06	2.67
2.5-MeV	0.00	0.00	0.02	0.00
Average first-wall heat flux, q_w (MW/m ²)	0.42	0.31	1.38	0.32
First-wall/blanket lifetime, $I_w\tau$ (MW yr/m ²)	13.	16.4	20.	13.
Blanket power density, P_{TH}/V_{BLK} (MW/m ³)	7.06	10.7	120.6	8.37
Thermal conversion efficiency, η_{TH}	0.49	0.46	0.44	0.49
Thermal power, P_{TH} (GWth)	2.60	2.57	2.97	2.53
Auxiliary site power, P_{AUX} (MW)	50.9	47.3	52.2	49.5
Primary loop pumping power (MW)	63.6	11.8	13.1	61.9
Gross electrical power, P_{ET} (GWe)	1.27	1.18	1.31	1.24
Net electrical power, P_E (GWe)	1	1	1	1
Recirculating power fraction, $\epsilon = 1/Q_E$	0.21	0.15	0.23	0.19
Net plant efficiency, $\eta_p = \eta_{TH}(1 - \epsilon)$	0.39	0.39	0.34	0.40
Mass power density, MPD (kWe/tonne)	71.7	92.6	88.8	111
Level of Safety Assurance, LSA	1	2	2	1

TABLE B3. Summary of ARIES Economic Parameters

Acct. No.	Account Title	ARIES			
		I'	II	III'	IV
		million		dollars	
20.	Land and land rights	10.4	10.4	10.4	10.4
21.	Structures and site facilities	245.2	366.4	333.4	245.3
22.	Reactor plant equipment (RPE)	1683.4	1361.8	1356.6	1302.3
22.1.1	First wall, Blanket, and Reflector	104.5	53.8	8.6	86.7
22.1.2	Shield	515.7	366.4	196.7	406.7
22.1.3	Magnets	436.7	205.8	268.9	222.6
22.1.4	Supplemental heating systems (CD)	155.2	194.3	529.2	175.7
22.1.5	Primary structure and support	71.4	35.3	50.5	36.5
22.1.6	Reactor vacuum systems	61.5	51.1	11.7	53.1
22.1.7	Power supply, switching, and ES	50.0	55.3	55.3	50.0
22.1.8	Impurity control	12.3	5.4	8.7	5.6
22.1.9	Direct energy conversion system	N/A	N/A	N/A	N/A
22.1.10	ECRH breakdown system	3.9	4.3	4.3	3.9
22.1	Reactor equipment	1411.3	971.7	1134.0	1040.9
22.2	Main Heat Transfer and Transport	119.2	231.9	68.6	117.3
23.	Turbine plant equipment (TPE)	254.5	279.8	323.3	249.3
24.	Electric plant equipment (EPE)	101.4	109.5	115.0	100.1
25.	Miscellaneous plant equipment (MPE)	54.7	55.5	58.8	53.8
26.	Special materials (SM)	0.6	14.8	0.6	0.6
90.	Total direct cost (TDC)	2350.5	2160.3	2198.5	1962.1
91.	Construction services and equipment	265.6	259.2	263.8	221.7
92.	Home office engineering and services	122.2	112.3	114.3	102.0
93.	Field office engineering and services	122.2	129.6	131.9	102.0
94.	Owner's costs	429.2	399.2	406.2	358.2
96.	Project contingency	482.1	516.5	525.6	402.4
97.	Interest during construction (IDC)	623.1	590.9	601.4	520.1
98.	Escalation during construction (EDC)	0.	0.	0.	0.
99.	Total capital cost (TC)	4395.0	4168.3	4241.9	3668.8
		\$/We	Constant	dollars	
[90]	Unit direct cost, UDC	2.35	2.16	2.20	1.96
[94]	Unit base cost, UBC	3.77	3.58	3.64	3.15
[99]	Unit total cost, UTC	4.40	4.17	4.24	3.67
		mill/kWeh	Constant	dollars	
	Capital return	63.8	60.5	61.6	53.3
[40-47,51]	O&M	7.5	9.2	9.2	7.5
[50]	First-wall/blanket replacement	5.0	3.6	0.01	6.6
	D&D	0.3	0.5	0.5	0.3
[02]	Fuel	0.03	0.03	17.5	0.03
	Cost of electricity, COE	76.6	73.8	88.8	67.7

APPENDIX C: Drawings of ARIES Fusion Power Cores

THE ARIES-I TOKAMAK FUSION POWER PLANT

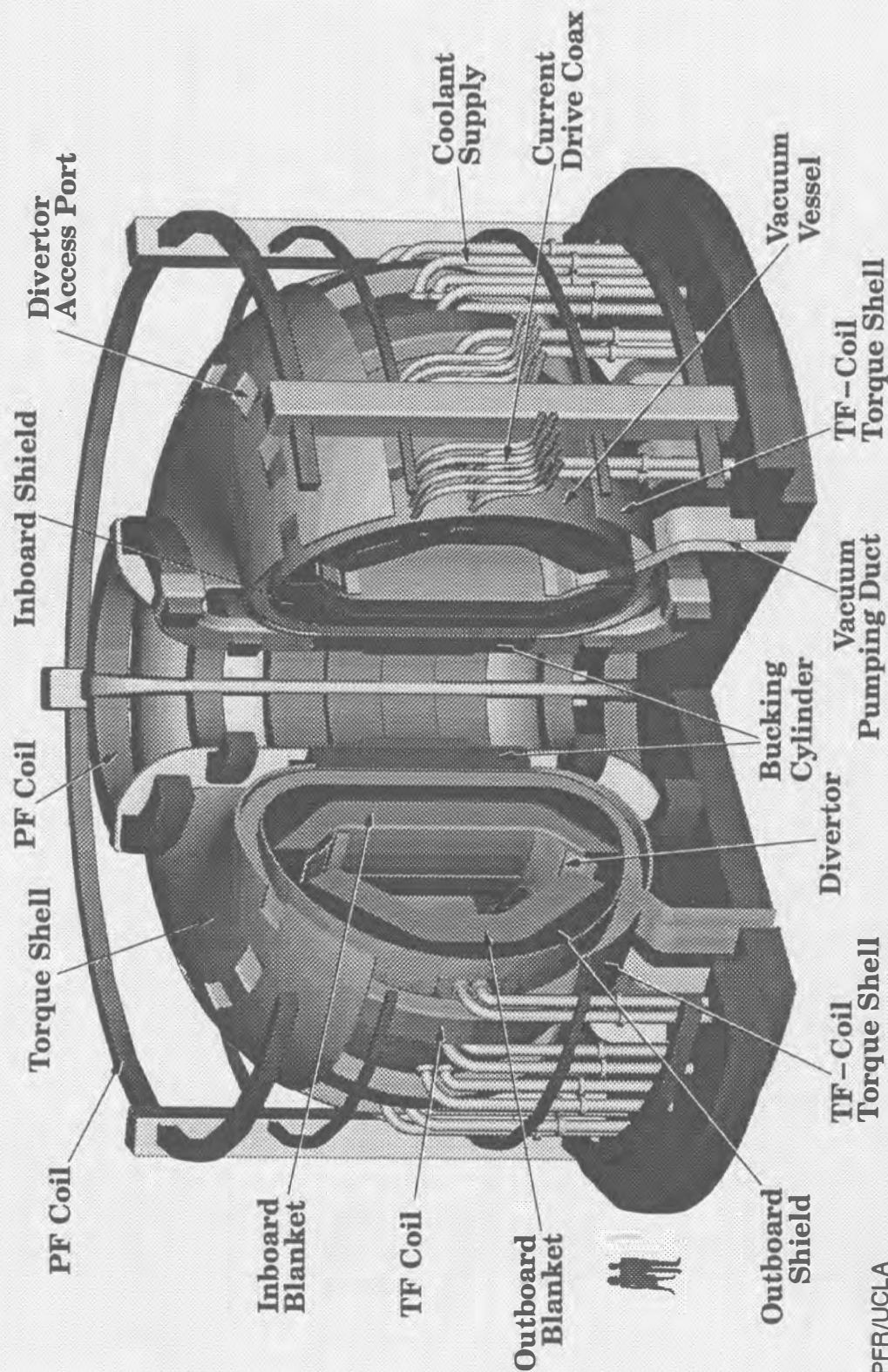


Fig. C1. Isometric view of ARIES-I Fusion Power Core.

IPFR/UCLA
SS: 9311_A1.OP

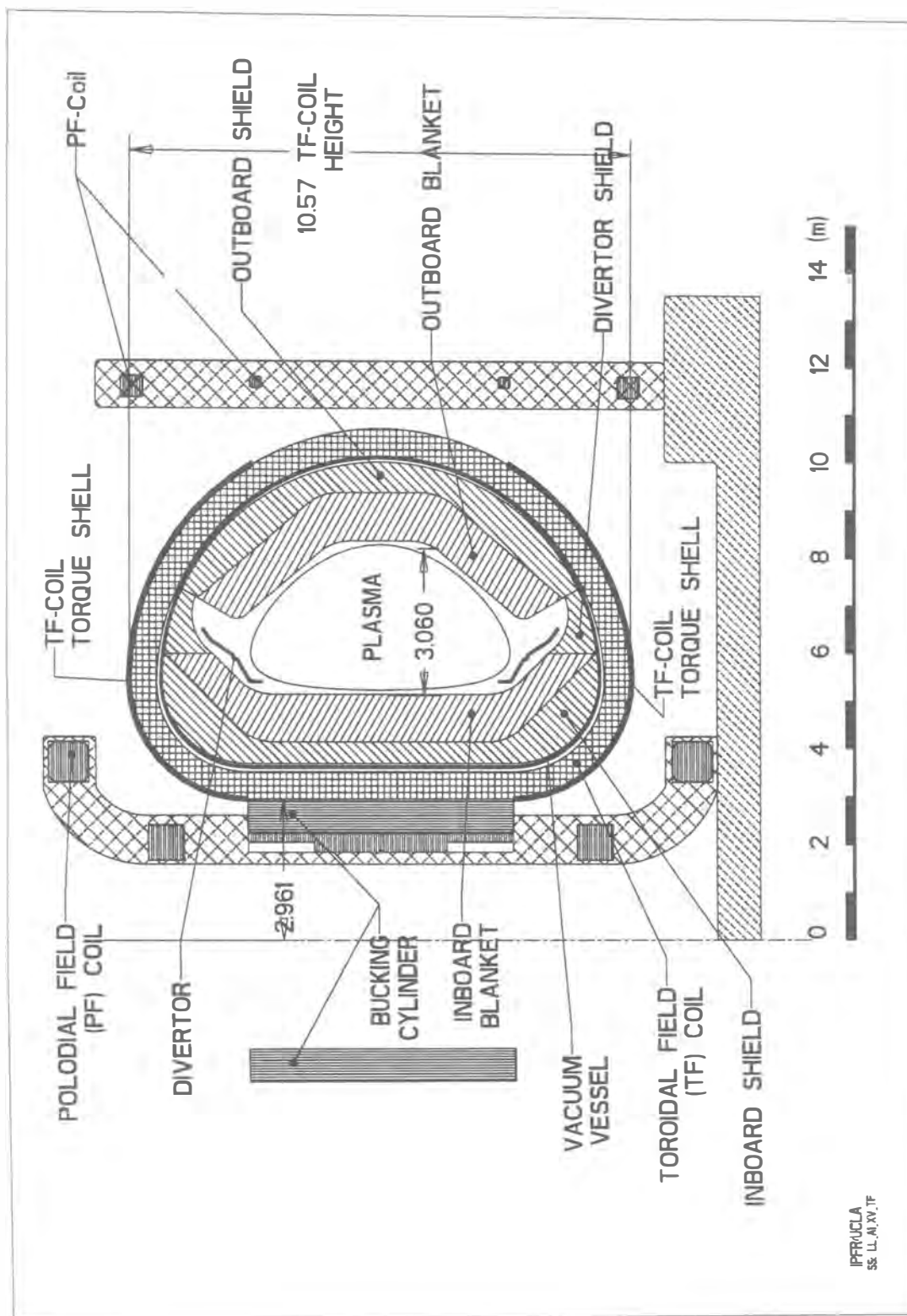


Fig. C2. Elevation view of ARIES-I Fusion Power Core.

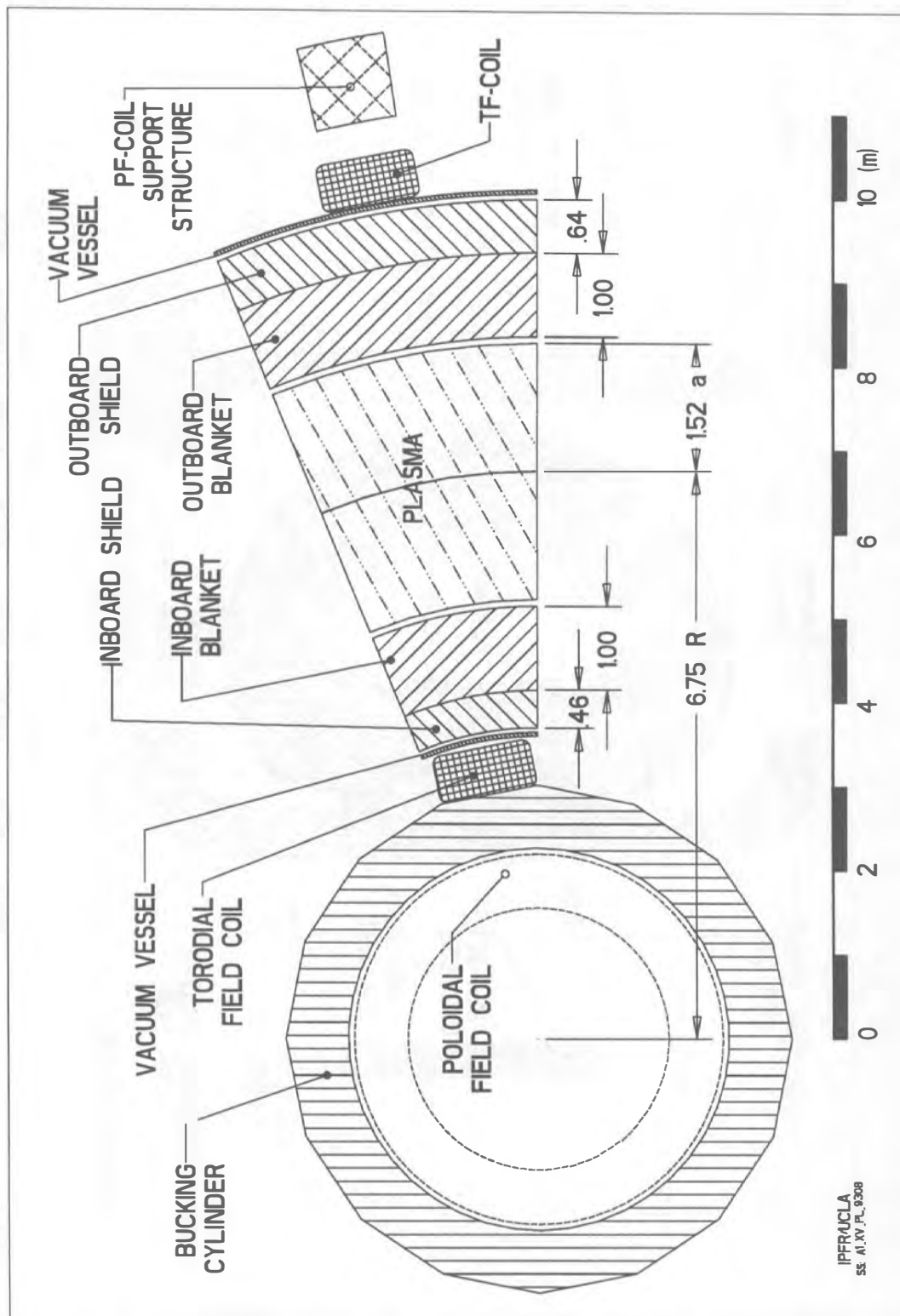


Fig. C3. Plan view of ARIES-I Fusion Power Core.

NOT AVAILABLE

Fig. C4. ARIES-II Isometric view of Fusion Power Core.

NOT AVAILABLE

Fig. C5. Elevation view of ARIES-II Fusion Power Core.

NOT AVAILABLE

Fig. C6. Plan view of ARIES-II Fusion Power Core.

THE ARIES-III TOKAMAK FUSION POWER PLANT

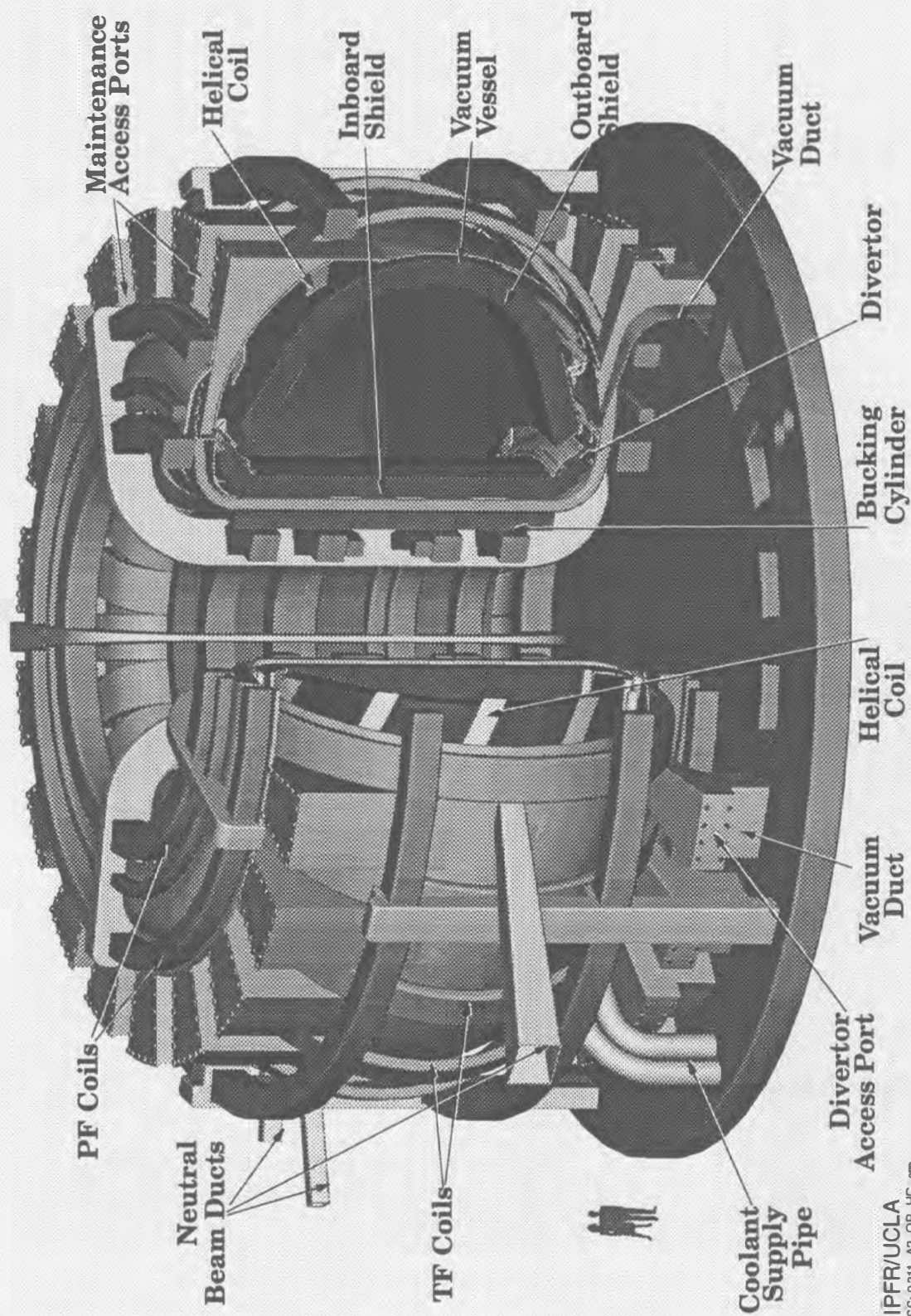


Fig. C7. Isometric view of ARIES-III Fusion Power Core.

IPFR/UCLA
SS: 9311_A3_OP_HC_op

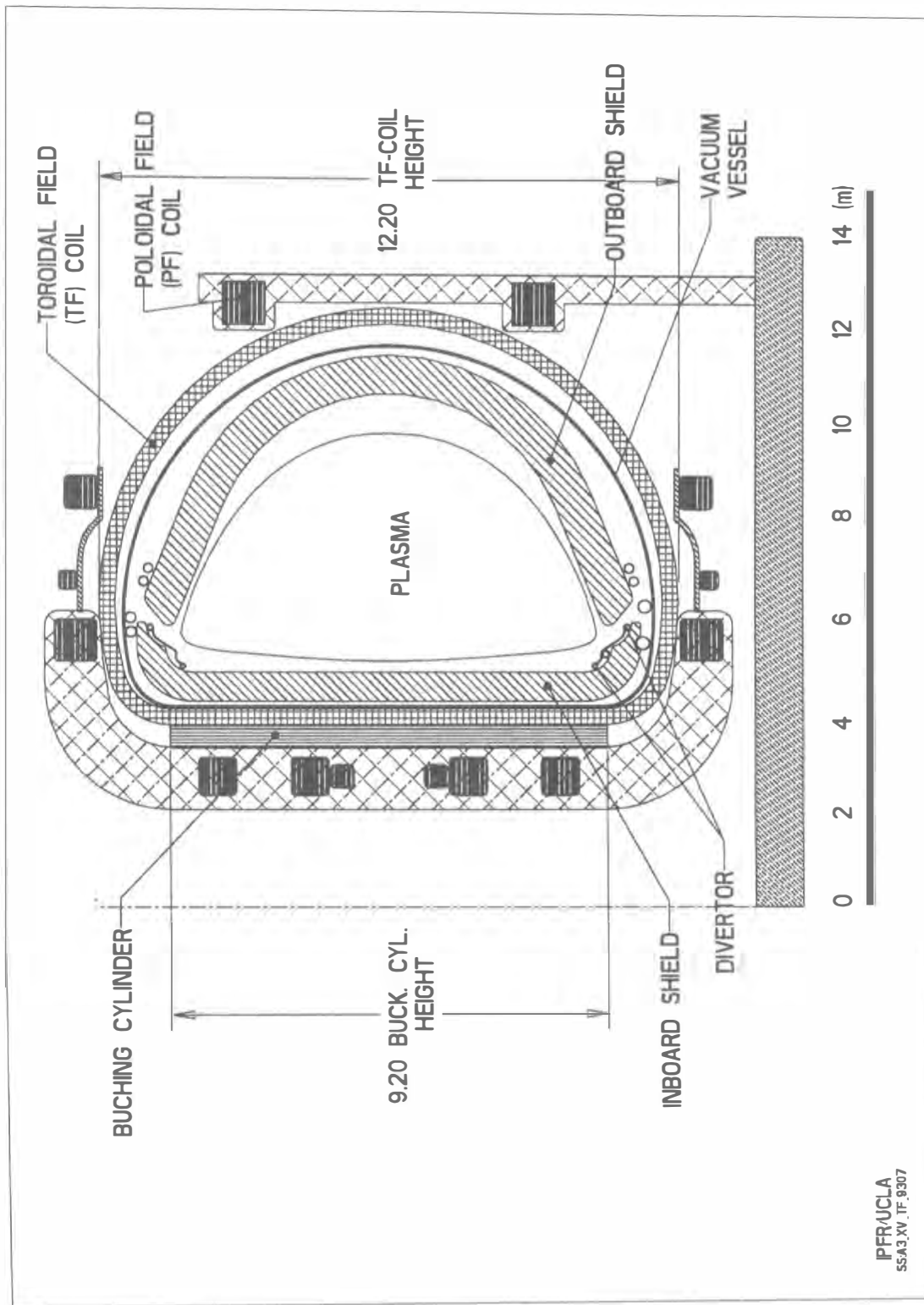


Fig. C8. Elevation view of ARIES-III Fusion Power Core.

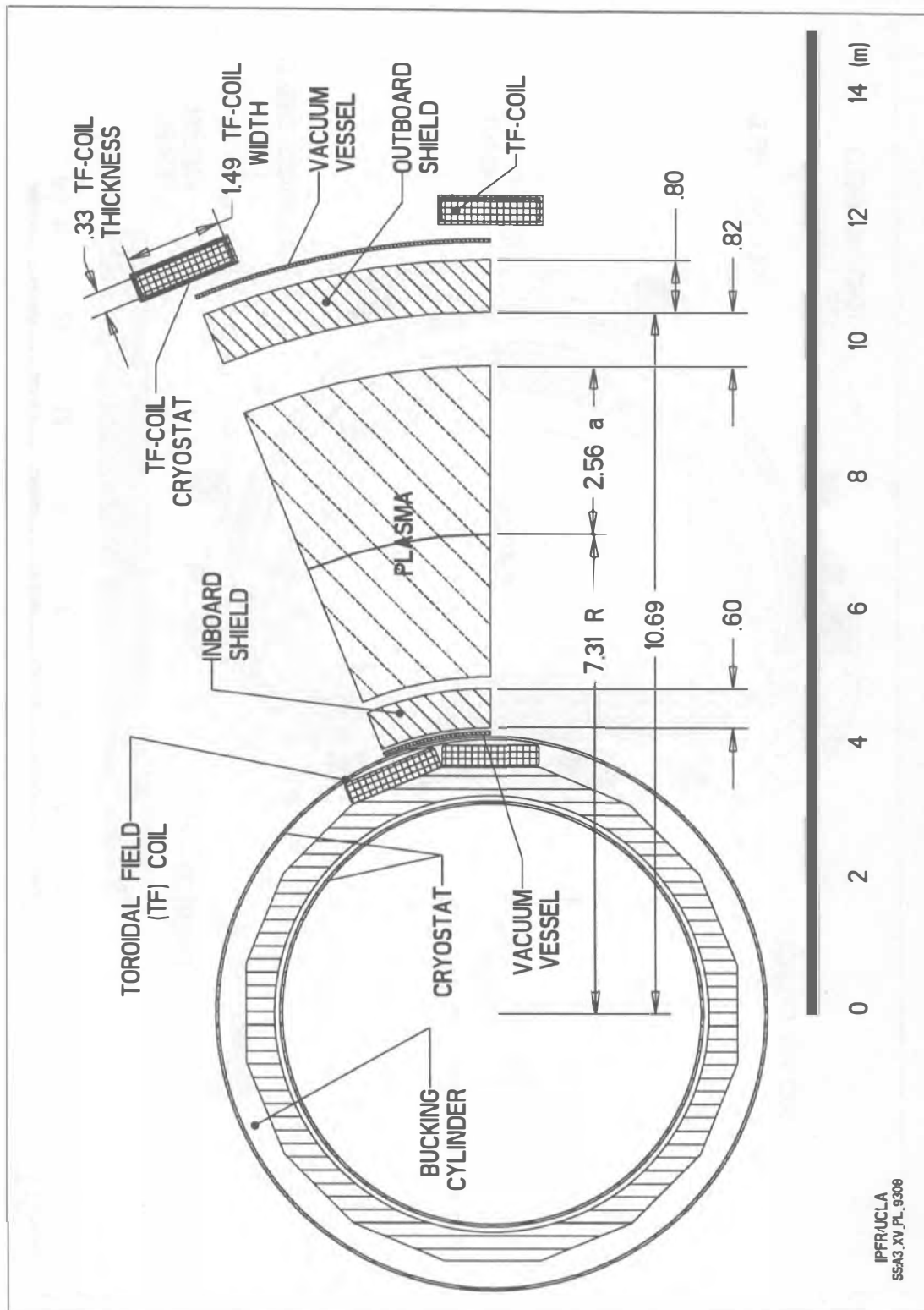


Fig. C9. Plan view of ARIES-III Fusion Power Core.

THE ARIES-IV TOKAMAK FUSION POWER PLANT

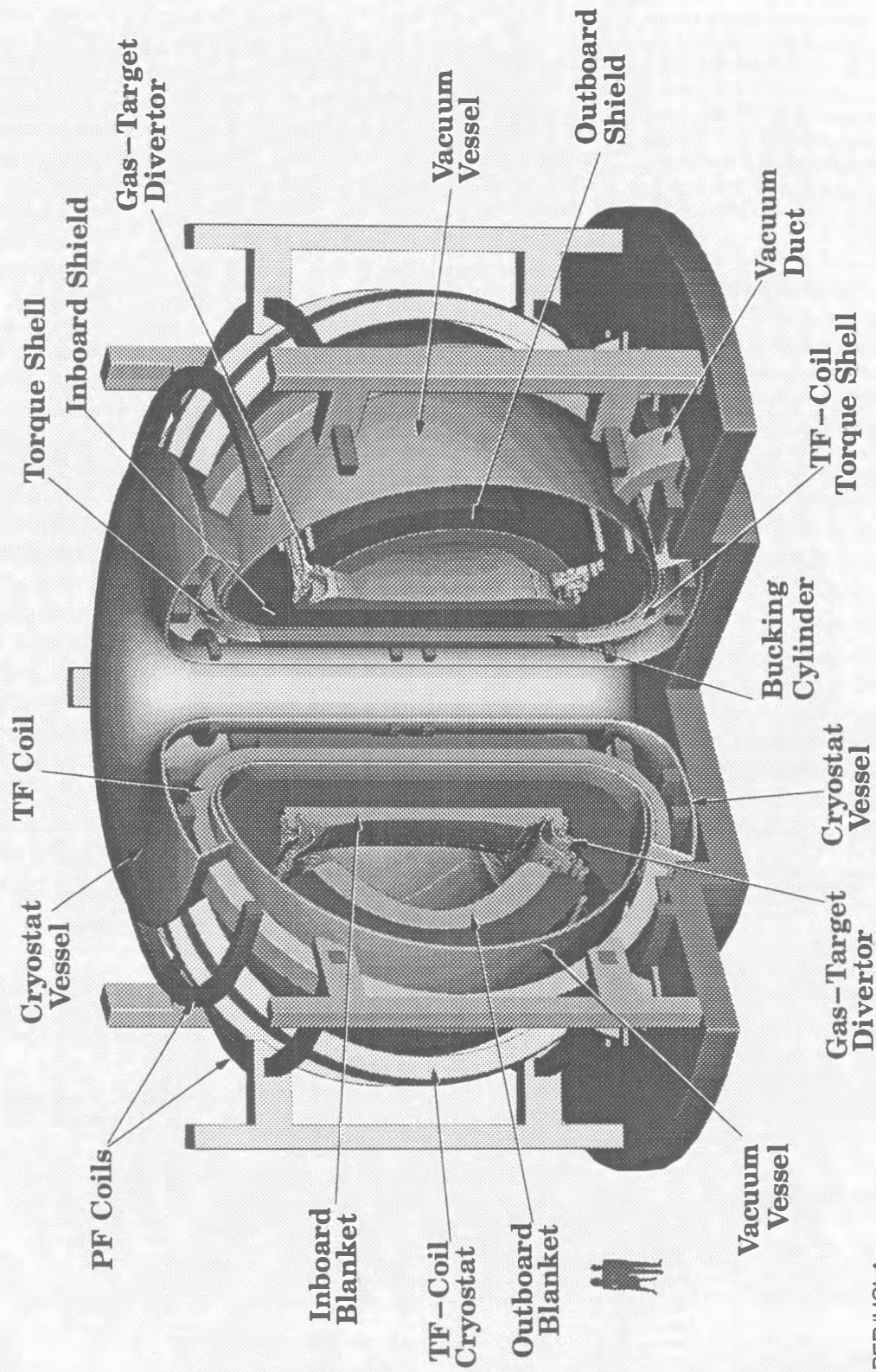


Fig. C10. Isometric view of ARIES-IV Fusion Power Core.

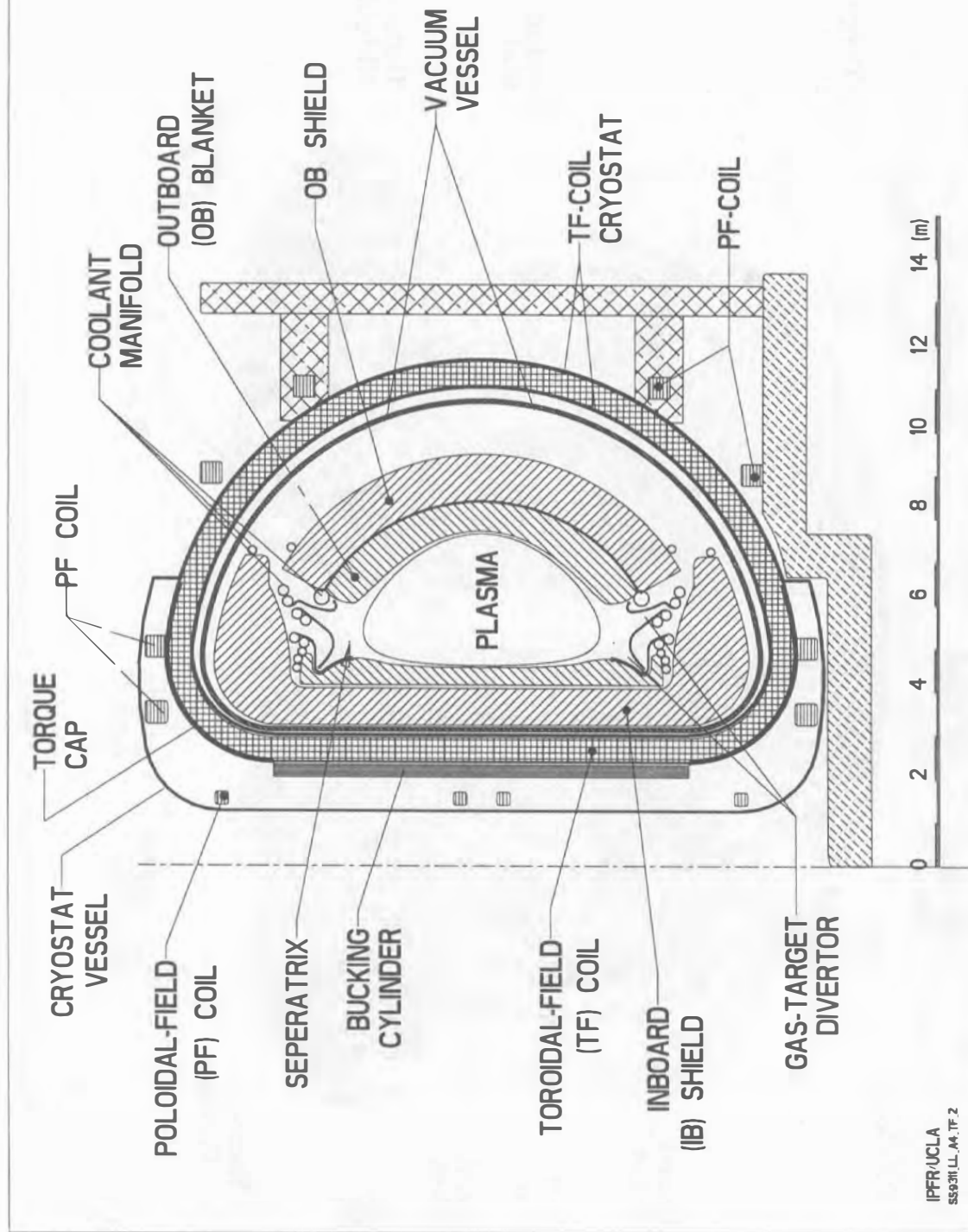


Fig. C11. Elevation view of ARIES-IV Fusion Power Core.

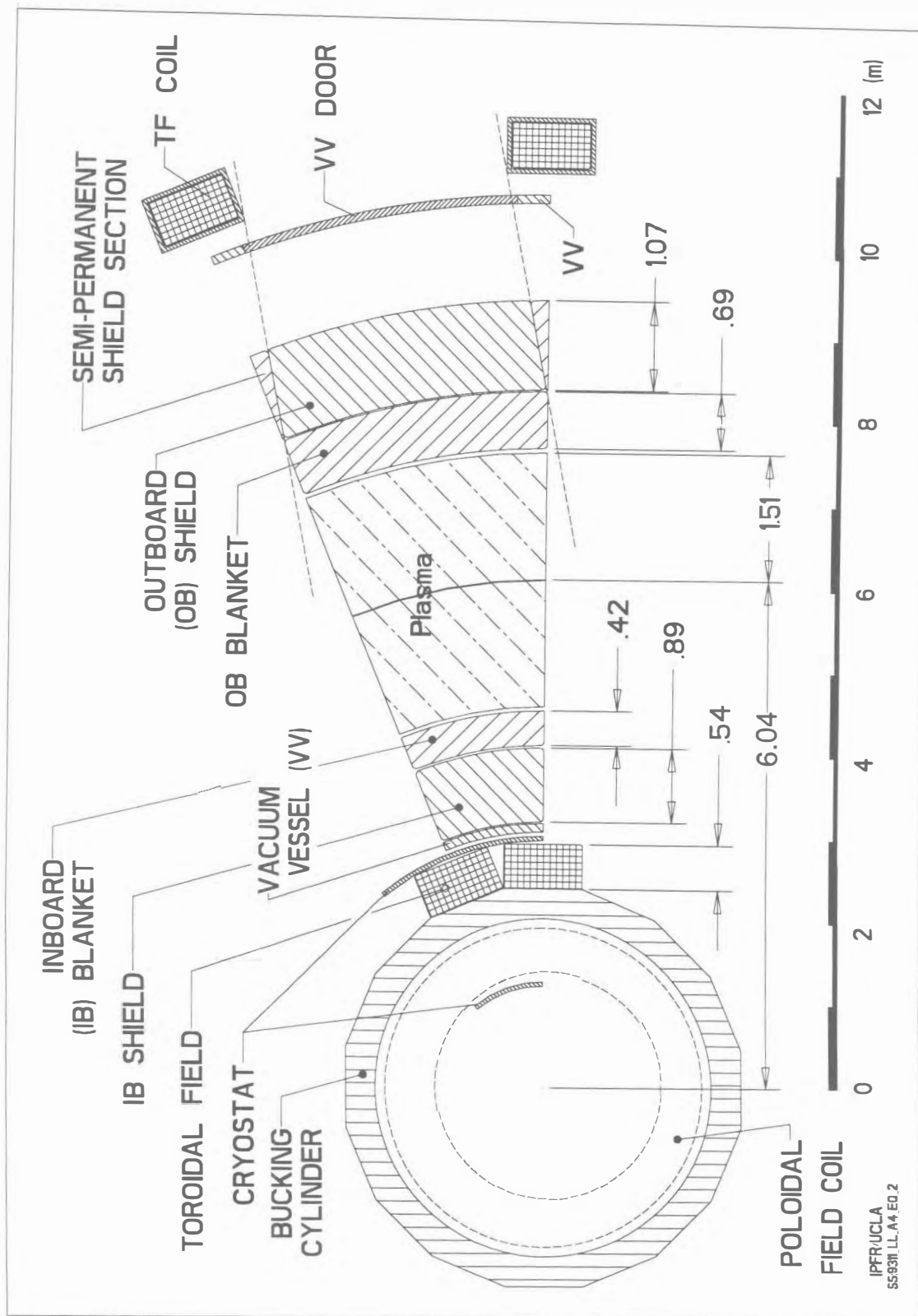


Fig. C12. Plan view of ARIES-IV Fusion Power Core.

Internal Distribution:

C. Barnes, P-1, E526
D. Barnes, T-15, B217
C. Bathke, TSA-3, F607
W. Davidson, TSA-3, F607
H. Dreicer, ADRE, A116
R. Krakowski, TSA-3, F607
R. Linford, EE-NS, H854
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