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# An advanced computational algorithm for systems analysis of tokamak power plants

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ABSTRACT

A new computational algorithm for tokamak power plant system analysis is being developed for the ARIES project. The objective of this algorithm is to explore the most influential parameters in the physical, technological and economic trade space related to the developmental transition from experimental facilities to viable commercial power plants. This endeavor is being pursued as a new approach to tokamak systems studies, which examines an expansive, multi-dimensional trade space as opposed to traditional sensitivity analyses about a baseline design point. The new ARIES systems code consists of adaptable modules which are built from a custom-made software toolbox using object-oriented programming. The physics module captures the current tokamak physics knowledge database including modeling of the most-current proposed burning plasma experiment design (FIRE). The engineering model accurately reflects the intent and design detail of the power core elements including accurate and adjustable 3D tokamak geometry and complete modeling of all the power core and ancillary systems. Existing physics and engineering models reflect both near-term as well as advanced technology solutions that have higher performance potential. To fully assess the impact of the range of physics and engineering implementations, the plant cost accounts have been revised to reflect a more functional cost structure, supported by an updated set of costing algorithms for the direct, indirect, and financial cost accounts. All of these features have been validated against the existing ARIES-AT baseline case. The present results demonstrate visualization techniques that provide an insight into trade space assessment of attractive steady-state tokamaks for commercial use.



## 1. Introduction

The Advanced Reactor Innovation and Evaluation Study (ARIES) [1] is a national, multi-institutional research program, which performs progressive, integrated design studies of the long-term fusion energy devices for general consumer utilities. The goal of this activity is to identify key research and development (R&D) directions and to provide visions for the US fusion program. An important route towards this goal is through systems studies of advanced fusion power plant concepts. A traditional approach to fusion power plant systems analysis is to design the optimal power plant and explore the sensitivity of this design to local perturbations in the most critical parameters [2]. This approach was exercised through all the past ARIES design studies, including the most recent steady state tokamak reactor ARIES-AT [3]. Traditionally, the ARIES systems code was utilized [4–7] within the ARIES project as a tool for parametric search of a design point [8] that yields the lowest cost of electricity for the prescribed constraints and operational parameters. However, the search for a single optimal point is not sufficient to provide an insight into a vast multi-dimensional space of possibly attractive "near-optimal" designs and may have a difficulty justifying the selection of that particular point.

Recently, the ARIES team has focused on identifying the R&D needs in transition from experimental tokamak facilities, such as ITER, to fully operational power plants (i.e., Demo and beyond). In this case, tradeoffs over wide regions of physics and engineering design parameters are sought. In order to fulfill this objective, a new systems code is being developed as a computational tool that integrates the state-of-the-art physics, engineering, and costing algorithms. The new structure of the systems code is modular

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and composed from a custom-made toolbox of generic, easy-to-assemble building blocks. The steady state plasma physics for advanced tokamaks is modeled by an algorithm that was already developed in order to examine the high field compact tokamak burning plasmas for the fusion ignition research experiment (FIRE) [9]. The reactor model includes the radial build, nuclear parameters, power core and energy conversion systems that are compatible to the ARIES-AT [10] but can easily be altered from this design. For example, the current tokamak model has an option of implementing different blanket concepts, such as the advanced $Pb-17Li + SiC_f/SiC$ concept and the dual coolant $Pb-17Li + FS + He$ concept, in order to assess the impact of blanket design on the technological and economic attractiveness of the power plant. The former blanket option was used with the ARIES-AT with liquid Pb–17Li as breeder and coolant. The latter option, also known as dual coolant lithium lead (DCLL) blanket, was developed using helium in the first wall in order to mitigate the MHD-induced pressure drop due to the circulation of high velocity liquid metal to cool the first wall (FW) in the presence of a magnetic field. The proposed solution was to use helium as a coolant for the FW and structural box and a lower velocity self-cooled Pb–17Li as a breeder. Both blanket concepts were analytically evaluated on a compact stellarator ARIES-CS [11] and their comparison revealed some economic penalties associated with the DCLL concept [11,12]. Those penalties include a thicker blanket and higher pumping costs due to the introduction of helium, as well as decreased passive safety rating, resulting in higher level of safety assurance. As a consequence, the total cost of the DCLL blanket was higher [12] for the compact stellarator, but no similar comparison exists for tokamaks at present.

The new tokamak model has a magnetic confinement system that resembles the one used for the ARIES-AT in geometry, while updated algorithms were used for the material composition, size and cost of two magnet options: low temperature superconducting magnet (~4.2 K) and high temperature superconducting magnet (~75 K).

The structural support of the toroidal field (TF) magnet is estimated by scaling from the finite element analysis reported in Ref. [13]. The breakdown of all the fusion power plant costing accounts was originally suggested by Schulte et al. [14], who introduced the direct and indirect cost accounts and defined some of the algorithms that are presently used. A complete and well-documented cost assessment was given by Waganer et al. [15] in the STARFIRE conceptual power plant study. The GENEROMAK report [16] developed a basis for a parametric reactor design with modeling algorithms based largely on STARFIRE [15]. The ESECOM study [17] was the first to employ safety assurance credit factors for use with design concepts employing advanced fuels or low activation materials to reduce capital costs on specific systems and subsytems. This credit concept evolved into the Level of Safety Assurance as first employed in ARIES-II, IV final report [18]. The costing accounts and the associated algorithms have been further updated through the 1990s–2000s ARIES design concepts, such as ARIES-I, II, IV, RS, SPPS, ST, and AT. A thorough revision of this costing breakdown is currently in progress in order to reflect a more functional cost structure.

The ARIES systems algorithm is outlined and compared to its predecessor code in Section 2. The plasma physics module of the code is described in Section 3. A detailed overview of the power core is given in Section 4, where special attention is paid to the radial build, magnetic confinement system and blanket options. The power flow is described in Section 5, with a detailed description of two power cycles associated with different blanket options. Filtering of tokamak power plants through different engineering criteria is outlined in Section 6. Costing algorithms are overviewed in Section 7, with a detailed account of all the components that comprise the cost of electricity. Example results that highlight the utility of the systems code are demonstrated in Section 8, followed by a discussion and guidelines for future development, given in Section.

## 2. ARIES systems code

### 2.1. Motivation and overall plan

During the past 20 years, the ARIES team has developed several advanced magnetic fusion concepts, including tokamaks (ARIES-I, ARIES-II&IV, ARIES-RS, ARIES-AT and Pulsar), the ARIES-ST spherical torus, the TITAN reversed-field pinch, and stellarators (SPPS and ARIES-CS). All of these concepts are derived from systems studies integrated with detailed off-line physics and engineering analyses, which utilized the most advanced known methods at the time. This approach will be retained in the future. However, several major deficiencies of the previous systems code will be addressed, such as outdated engineering and costing models, lack of modularity, difficulty of upgrading to new features and limited approach to finding the optimal operating point.

The new ARIES systems code is being written in order to generate an updated, more accurate model of an advanced, steady state D-T fuelled tokamak. In addition to building the new algorithms, a new computational strategy is being devised in order to accommodate the change of focus from analyzing a single data point to investigating a wide, multi-dimensional operational design space. The new objective is to identify tradeoffs in operating parameters that will lead to highly desirable tokamak solutions that might lessen or eliminate major constraints. The new systems code has a number of advantages compared to the former algorithm:

- All the modules of the new code are generated from a custom-made, general purpose toolbox, which is built to allow an easy way to assemble an arbitrary, but viable tokamak model.
- In order to efficiently generate a large database of tokamak solutions, physics and engineering filters are implemented at early stages of calculation to eliminate any non-valid design points.
- A new physics module derived from the proposed FIRE design study implements the most current knowledge in simulating advanced steady state plasmas.
- Engineering algorithms provide a complete update of the power core elements with 3D geometry and a more realistic power flow.
- Costing algorithms are updated in order to reflect the latest costing methodology.
- 2D and 3D visualization techniques are developed and utilized in order to provide an insight into parametric design space of advanced tokamaks.

### 2.2. Algorithm layout

The ARIES systems code consists of three distinctive modules, which are physics, engineering and costing, as shown in Fig. 1. The physics module generates a large set of viable operating plasmas for advanced, high fusion performance tokamaks. The engineering module creates the inboard, outboard and top/bottom radial builds for the blanket, divertor, shield, vacuum vessel and TF coils, a power extraction and conversion system for given plasma, 3D power core configuration, and the power flow model from nuclear fusion power to net electric power. The costing module estimates the direct and indirect capital cost of the entire plant including more detailed costs for the power core. These capital costs are converted to annualized costs and added to the annual costs for operations and maintenance, fuel, scheduled component replacement, and decommissioning to determine the cost of electricity. The cost of electricity is the figure of merit and the final output of the systems code.