A detailed and integrated study of compact stellarator configurations, ARIES-CS, was performed to advance our understanding of attractive compact stellarator power plants and to define key R&D areas. This paper summarizes the result of the ARIES-CS study.

The first major goal of the ARIES-CS research was to investigate whether stellarator power plants can be made to be similar in size to advanced tokamak variants. Analyses of tokamak power plants have shown that the cost of electricity (COE) is reduced substantially when the machine size is reduced, with this reduction in COE “saturating” when the average plasma radius becomes roughly similar to that of plasma-coil spacing. In addition to the reduction in cost, smaller power plants would generate a smaller amount of waste as most of the rad-waste is due to permanent components. We pursued three avenues to reduce the ARIES-CS size: a) Develop stellarator configuration with lower aspect ratios; b) For a given stellarator configuration (i.e., plasma aspect ratio), increase the coil-plasma spacing (i.e., lower coil/plasma aspect ratio); and c) Develop engineering options to reduce the required minimum distance between the plasma and the coil ($\Delta_{\text{min}}$).

We focused our analysis on quasi-axisymmetric (QAS) configurations as they are able to operate at a low plasma aspect ratio (~4-5). W7-X –class configurations have been extensively studied previously (HSR-4 and HSR-5). We also spent some effort on optimizing configurations with quasi-helical symmetry; however, we could not achieve desirable low-aspect ratio configurations. Because of the large research effort spent in developing the NCSX configuration, the ARIES-CS configurations naturally evolved from NCSX equilibrium. The major critical issue of this configuration for a fusion plasma is its high $\alpha$-particle loss rate. Our efforts to reduce $\alpha$-particle loss rate- led to new criteria for optimizing QAS configuration. We also developed two new classes of QAS configuration in which strict adherence to linear, ideal MHD stability constraints were relaxed as recently achieved experimental values for $\beta$ are higher than those predicted from linear stability theory. The first class of the new configurations is MHH2, which aims at developing a very low aspect ratio geometry with relatively simpler coils. The second class, SNS, is aimed at developing a configuration with excellent flux surface quality and nearly flat rotational transform to explore how good and robust flux surfaces can be designed. For each case, we develop coil designs in order to maximize plasma/coil spacing.

Previous studies had assumed that the radial build of the fusion core is uniform around the plasma. This is not an optimum approach as the external coils are close to the plasma only in
certain locations (~8% of first-wall surface area) for NCSX-like configurations. A novel approach was developed to downsize the blanket and utilize a highly efficient WC-based shield in the space-constrained regions where plasma is close to the coil. The special modules in these regions utilize a non-uniform blanket and a WC-shield, optimized to provide shielding comparable to a regular breeding module but with a much reduced module radial thickness (e.g., the typical plasma-to-mid-coil radial thickness for a regular breeding module is about 1.79 m, but is only 1.31 m for an optimized module with a reduced breeding zone but with similar shielding properties). The total tritium breeding including all modules is ~1.1.

Stellarator fusion core components would have complex shapes and geometry. This complexity imposes severe constraints on fusion core components such as non-uniform heat, particle, and neutron fluxes; accessibility for assembly and maintenance; and feasibility and cost of manufacturing. The second major goal of the ARIES-CS study was to understand and quantify, as much as possible, the impact of complex shape and geometry of fusion core components. First, it became evident early on that the 3-D shape of the plasma and the coil (and the components between them) necessitates 3-D analyses of various components -- typical correlations and insight developed for axisymmetric fusion devices are not appropriate for stellarator geometry. As such, we directly used 3-D CAD models in many of our analyses. Moreover, we found that the results are quite sensitive to the details of 3-D shape of components and slight variations can result in substantial changes. Second, we have found that engineering configuration as well as assembly and maintenance procedures are key elements in optimizing a compact stellarator – in some cases, these issues determine the choice of technologies available. Examples include the selected port-based maintenance scheme which requires a compatible internal design of the fusion core and led to the choice of a ferritic-steel, dual-coolant blanket; and the irregular shape of the superconducting coil that necessitates development of inorganic insulators for high-field magnets.

This paper summarizes the ARIES investigation of compact stellarator power plants and the key findings. Trade-offs among physics and engineering constraints performed through a cost-optimization systems code are highlighted; key design features and analyses are described; and the major R&D issues are discussed.