

Evaluation Report of the Peer Review of the Fusion Advanced Design (System Studies) Enabling Technology Program

General Remarks

In an overall assessment of the ARIES Advanced Design Program one should emphasize that, since its inception in the 1980s, this program has played a very essential role in shaping the communities' view of what goals the fusion science and technology program is ultimately seeking. The ARIES Team has solidly established itself as a national resource acting as an "honest broker" which the community looks towards to evaluate the relative promise of different approaches to fusion energy power systems. The ARIES Program has played this role for more than a decade, incorporating many power plant studies, without serious concerns being raised about objectivity or technical approach. This provides clear evidence of the excellent technical quality of their work and the high professional standards of the scientists and engineers who make up the ARIES national team. It is essential to the fusion energy sciences program that a program of this type be maintained.

Quality and Innovation

1. *How does the research conducted in this enabling technology program compare with other research in its field and evaluate it in terms of its scientific/technical merit and originality?*

While other nations have fusion power plant design groups, the ARIES program is unique in the world in assembling a national team of experts who work on the full scientific and technical integration of a power plant vision. Consequently, the quality of the power plant design studies produced by the ARIES Program is the very best in the world. The team members have a long-term involvement in the program that provides for continuity in approach and standards, and makes comparisons between the various studies more quantitative.

In the course of the recent power plant design studies, the ARIES program has made a number of significant original contributions to the field. From the technology perspective this includes: pioneering work in the use of silicon carbide composites as major structural elements in the power plant; adaptation of innovative manufacturing techniques to greatly reduce the cost of major systems; development of innovative assembly/disassembly techniques; high-temperature thermodynamic cycles; advanced manufacturing; self cooled lithium-lead blankets; and low activation designs, etc. Original physics contributions include identification of specific physics paradigms for approaches to a fusion power system (e.g. ARIES-I, a high field, first-stability regime tokamak; ARIES II/IV, a second-stability regime tokamak; ARIES-RS, a reversed shear tokamak). The self-consistent integration of a detailed physics model of the plasma configuration with the technical embodiment of the power plant design makes the ARIES power plant studies extremely valuable in assessing the potential for specific approaches to fusion power systems. In addition, the ARIES power plant studies have identified and provided a quantitative analysis of 'high-leverage' issues in plant design including the trade-off between high beta and high bootstrap fraction, extreme shaping and engineering constraints, as well as technical limitations in pulsed designs, and relative costs of non-inductive current drive.

Being a national team effort that draws on the resources of the entire U.S. fusion program further distinguishes the ARIES program in comparison to other reactor design efforts in Europe and Japan. Evidence was presented to the reviewers that Japanese teams, in particular, have begun to adopt the ARIES approach to reactor design that was standard in ARIES work a decade ago.

2. *Are the scientific methods and approaches used the most effective in conducting the research and in addressing the issues being faced by the Fusion Energy Sciences program?*

Due to budget limitations, the ARIES Team has had to prioritize their efforts and has done so in a responsible manner emphasizing important scientific and technical issues. In the course of prioritizing their efforts, they have had to rely upon existing tools or have used simplified models (e.g. confinement databases, ray-tracing models), rather than invest in tool or model development (e.g. integrated predictive modeling or full wave models). In other areas, they have encouraged and facilitated the work by the community to improve existing codes and resolve differences between codes, for instance in the areas of MHD stability analysis and high-beta equilibrium, as well as applied their own limited resources to this effort.

In the design of the fusion plasma core of a power plant, the approach followed by the ARIES program is to apply state-of-the-art models for equilibrium, stability, bootstrap current, radio-frequency (rf) driven current, transport, and the edge plasma & divertor, backed up where possible by use of the latest experimental results. This approach is technically sound and highly effective. Because the ARIES power plant studies necessarily need to be forward looking in both physics and engineering design, subjective choices will always need to be made in extrapolating present understanding and experience. Extrapolations adopted by the ARIES program have always been based on either experimental results or well-grounded theoretical predictions. How aggressive to be in these extrapolations will always be a matter of some debate. On the whole, the ARIES program has done a good job of looking ahead, but not at the cost of damaged design credibility.

Could the ARIES program improve on their methods and approach? Yes, but to do so would require additional manpower and computational resources. A few examples (which are well known to the ARIES team) would include: (i) inclusion of the most accurate bootstrap current model in the low aspect ratio calculation of ARIES-ST; (ii) use of developing models for active feedback control systems of the $n=1$ kink mode in ARIES-RS, ARIES-ST, and ARIES-AT; (iii) use of a broader range of equilibrium and stability codes such as GATO, DECON, and MARS; and (iv) use of a broader range of rf heating and current drive models. For the most part, the ARIES team has employed modeling tools familiar to and in many cases developed (or improved) by the participants. Expansion of this tool set would require involvement of new personnel and investment of time. In some cases the ARIES program has indicated it plans to extend its capability (e.g. use of MARS for resistive wall mode analysis).

3. *Is the documentation and reporting of the research, the technical approach and the scientific results complete and of high quality?*

The ARIES Team has extensively published the results of their work. Their results are widely cited throughout the community and respected. The review team could not locate all of the final design reports on the web. One of the primary archival records of the ARIES design studies is the publication of “final design reports” which provide a comprehensive record of the design study and all key assumptions and methodologies used. In checking the ARIES web site, it was not always clear where to access the final reports. Current links to the best source of this documentation should be provided on the web page. It is important to publish the final design reports upon completion of the study.

Another suggestion, for improving the effectiveness of the findings of the ARIES program, is to more clearly identify and bring to the attention of the community high leverage “gaps” in either understanding or tools that are uncovered in the course of their power plant studies. Perhaps a short “Critical R&D” list could be put up on the ARIES web site and discussed at appropriate workshops and town meetings. This would help the community understand where important information is needed and may also stimulate “pro bono” contributions or help to identify potential new team members.

Resourcefulness in Resource Management

1. *Are resources (personnel, access, etc.) utilized in the most effective and efficient manner possible including leveraging and teaming with other fusion and non-fusion programs both domestically and internationally?*

Given the broad based national team comprising 12 institutions, the ARIES program has done an excellent job in setting up an efficient, very flat management structure which allows virtually all its resources to be devoted to carrying out its technical activities. The use of team members who are only involved in the ARIES program on a part-time basis, and spend the remainder of their time in other fusion or technical activities, is a highly effective way to leverage against expertise developed as part of other activities in the fusion program. This structure of largely part-time participants also broadens the communication base of the ARIES program with the fusion community. The use of international visitors has also been a valuable link to other power plant studies groups in Europe and Japan.

This is a highly effective, well-managed team effort with an experienced and effective core group (about 35 strong). As needed, the group draws on expertise from other parts of the community and maintains close contact with the larger fusion energy sciences community. Leveraging is also evident in many technologies not currently under development in the US fusion program. These include the development of silicon carbide composites (aerospace and automotive industries) high-temperature Brayton cycles (nuclear industry) and advanced low-cost methods for component fabrication (aerospace). This is clearly an effort where the whole is greater than the sum of the parts. While the team program effectively utilizes regularly scheduled project meetings, PAC reviews and input from advocacy groups to guide its work, it would be advantageous to solicit input into the design product from experts not associated with the program within the wider fusion sciences community.

The ARIES Team has effectively used the resources within the community and coupled to the community. The management and oversight costs are kept low and broad community participation has been encouraged. The involvement of industry, especially in the areas of advanced manufacturing techniques, is highly commended for bringing attention to the fusion program new and important developments that can have important long-term impacts. The use of workshops, that bring both U.S. and international experts together, is a very effective use of resources. While some of the ARIES studies have been peer-reviewed, that does not appear to be the present practice. Peer-review of the studies may be beneficial in engaging a broader part of the community in the program and obtaining an assessment of the studies. Such a process would be valuable in documenting comments by advocates and critics for a given concept or study, and giving the Team an opportunity to respond. This should improve the studies and the documentation for future reference.

One problem that has been faced by the ARIES program is how to evolve its skill mix as program needs change in an environment of declining budgets. This frequently can mean hard choices between loss of expertise that may be needed in the longer term and bringing in needed new expertise. As the ARIES program goes forward with plans for a study of IFE power plant systems, followed by innovative magnetic confinement concepts (RFP and compact stellarator), this problem will likely get worse. The ARIES program will need to work closely with the OFES and VLT Director to try to accommodate personnel shifts in the next few years, so that critical expertise is not lost from this valuable activity.

2. *Given the challenge in making fusion work, is this program making progress in addressing the issues and problems that they are facing?*

As described above in the Quality and Innovation section, the ARIES program has established a solid record of contributions by identifying the targets that the fusion program is working towards in developing practical fusion energy systems. The ARIES power plant design studies have served as internationally recognized benchmarks. In the most recent series of studies (ARIES-RS, ARIES-ST, and ARIES-AT) the introduction of advanced manufacturing, innovative approaches to assembly and maintenance, and a state-of-the-art fusion plasma core has resulted in dramatic improvements in the projected attractiveness of magnetic fusion power systems.

The team has made significant progress in identifying and understanding key issues and problems and then in finding possible solutions. Over the years, there has been steady progress in finding ways to reduce the cost of electricity, improve reliability of components, and enhance the safety of fusion systems. Several ideas, which have originated with the ARIES team, have been taken up by other areas of the fusion program, and led to improved performance.

There are a few areas where additional analysis would be desirable. Examples are:

1. Disruption analysis. A tokamak power plant is expected to have very few disruptions, but the plant should be able to recover from a single disruption with a minimum interruption in operation. The transient stresses in the structure, including those from halo currents, determine the level of damage to the system.
2. Penetration analysis. Often the limits of operation are determined by the influence of penetrations. Flow paths must be altered, extra nuclear shielding is required, and different materials may be used.

3. Out-of-core materials considerations. It is sometimes desirable to transition to another material(s) outside the core for cost, safety, or performance reasons. For example, the vanadium structure considered in ARIES-RS is expensive, and a transition to stainless steel may be desirable outside the radiation zone. There are a number of issues with joints, allowable temperatures, etc. that could be addressed.

Relevance and Impact

1. *Is the work that is conducted supportive of, consistent with and relevant to the current goals of the Fusion Energy Sciences program? Is it contributing to the knowledge base needed for an economically and environmentally attractive energy source?*

The mission of the Fusion Energy Sciences Program as recommended by FESAC and adopted by the DOE OFES is: “Advance plasma science, fusion science, and fusion technology – the knowledge base needed for an economically and environmentally attractive fusion energy source.” The ARIES program plays a unique and important role in advancing this knowledge base by illuminating relatively complete and self-consistent visions of the ultimate objective of an economically and environmentally attractive energy source. The ARIES program provides critical information on what advances in science and/or technology have the highest leverage for improving a candidate approach to a fusion power system, and also identifies important gaps in our present knowledge base. Without these periodic studies of “where we are going” using reasonable extrapolations of our present level of scientific and technical understanding, making choices of where to concentrate our limited research resources would be done less effectively.

2. *Does the work that is conducted have significant and positive impact or influence on other fusion program elements, both domestically and internationally, and on other scientific and technical fields? Are there any other benefits, which are accruing from this work such as spin-offs or education of students?*

The ARIES program has had significant and broad based impact on the fusion program. Some examples include the previously cited contributions: (i) use of SiC composites as major structural elements in the power plant driving R&D in the materials and technology part of the fusion program; and (ii) the identification of specific physics paradigms for approaches to a fusion power system (e.g. ARIES-I: high field, first-stability regime tokamak; ARIES II/IV: second-stability regime tokamak; ARIES-RS: reversed-shear tokamak) which has helped shape the approach taken in the effort to improve the tokamak concept. In addition, the adoption of the Brayton cycle for high efficiency power conversion has reshaped the view of the potential attractiveness of tokamak based fusion energy systems. This focus of the US program on improving the attractiveness of the end product combined with the thoroughness of the ARIES designs has had the effect of shaping international opinion on relative emphasis in fusion R&D.

Looking at the impact and influence of the ARIES program outside of the fusion program, the electric utilities in the United States have voiced doubts in the past about the practicality and reliability of our vision of fusion energy systems. The ARIES program had allowed reviews of their improved designs by representatives of the electric utility community with positive impact on their view of fusion energy. This was carried out most recently for the ARIES-RS study. One recommendation is that such a utility review be organized to assess the improvements offered by the most recent ARIES-ST and ARIES-AT designs that have improved cost of electricity, maintenance, environmental impact, and expected availability.