STATE-OF-THE-ART 3-D ASSESSMENT OF ELEMENTS DEGRADING TBR OF ARIES-ACT SiC/LiPb BLANKET

L. El-Guebaly, A. Jaber, L. Mynsberge and the ARIES-ACT Team

University of Wisconsin, 1500 Engineering Dr., Madison, WI 53706, USA, elguebaly@engr.wisc.edu, ajaber@wisc.edu, lmynsberge@wisc.edu

Just recently, the ARIES team completed the detailed design of ARIES-ACT-1 with aggressive physics and advanced SiC technology. The ability of the SiC/LiPb blanket to provide tritium self-sufficiency was among the important issues investigated in detail. To pinpoint the design elements that degrade the breeding the most, we developed a novel stepwise approach that involves building the CAD model from scratch, and, in multiple steps, adding the internals/externals of the blanket. At each step, the impact on the tritium breeding ratio (TBR) was recorded to identify the more damaging/enhancing conditions or changes to the tritium breeding. The TBR approaches 1.8 for an ideal system, and then degrades to 1.05 for the ARIES-ACT-1 reference design. This paper sheds light on several breeding-related issues that puzzled the fusion community for decades and gives insight about the impact on TBR of the individual blanket internals as well as other essential parts of the tokamak.

I. INTRODUCTION

Several breeding-related questions have been puzzling the fusion community for decades: How does the blanket structure (first wall, side, and back walls, cooling channels, etc.) degrade the breeding? Which change to the blanket thickness and/or Li enrichment is more enhancing to the breeding? How does the advanced physics (that requires embedding stabilizing shells within the blanket) degrade the breeding? Could the required tritium breeding ratio (TBR) be achieved in the presence of several design elements (such as plasma heating and current drive ports) that compete for the best available space for breeding? Will the blanket over-breed or under-breed in the presence of several uncertainties in the operating system? Past studies made several attempts to answer some questions[1] by addressing individual issues – one at a time. However, there are still many remaining questions regarding the inter-dependence and synergistic impact of the various elements on breeding and the degree of confidence in the single-effect analysis. Our state-of-the-art 3-D analysis examined almost all questions collectively in an integral fashion.

Due to the availability of sophisticated 3-D neutronics codes, we were able to address many breeding-related questions within the framework of the most recent ARIES series of aggressive and conservative tokamaks (ACT).[2] The Computational Nuclear Engineering Research Group (CNERG) at the University of Wisconsin has developed the most innovative computational tool in recent years. This tool has overcome a major limitation in the 3-D nuclear analysis, permitting fully accurate modeling of complex devices by integrating the computer-aided design (CAD) geometry directly with the 3-D MCNP code,[3] allowing more accurate 3-D modeling in much less time than was previously possible.[4-6] The newly developed Direct Accelerated Geometry Monte Carlo (DAGMC) code[7] facilitates this process. In addition, to point out the terms that contribute to a decrease/increase in TBR of any blanket design, we also developed a novel approach[8] that allows adding the various blanket components "step-by-step" (e.g., first wall, side/top/bottom/back walls, cooling channels, stabilizing shells, assembly gaps, penetrations, etc.) and evaluating the impact of each component on the TBR. The combined CAD-coupling and stepwise approaches have been applied to the ARIES-ACT-1 SiC/LiPb blanket concept, as previously applied to the dual-cooled LiPb blanket concept.[8]

The ARIES-ACT designs require the calculated TBR to be 1.05 for the LiPb system. The 5% breeding margin is design dependent and evolves with time.[1] It accounts for known deficiencies in nuclear data and modeling and for the tritium bred in excess of the T consumed in the plasma to mainly provide the startup inventory for a new power plant.[1,8] In order to achieve the required TBR with sufficient precision during plant operation and to overcome the challenges of dealing with tritium-related uncertainties in several subsystems, an adjustment of the TBR is highly recommended for all LiPb designs through online control of the Li enrichment.[1,9] This suggests operating the blanket with ^{6}Li enrichments less than 90%. Only in recent year, such a restriction on the ^{6}Li enrichment became an essential design requirement particularly for ARIES designs employing the LiPb as the main breeder.

II. DESIGN DESCRIPTION AND 3-D TBR MODEL

A future hope for fusion is the prospect of using SiC/SiC composites as the main structure for a very high-temperature blanket (> 1000^{o}C) that offer high thermal conversion efficiency (> 55%) and upgrade the economic performance. Along this line, the ARIES-ACT-1 first wall (FW) and blanket structure are made of SiC/SiC composites while the LiPb breeder/coolant flows vertically in several channels.[10] An isometric view of ARIES-ACT-1 is shown in Fig. 1 with the main components identified. The major and minor radii for this interim design are 5.5 and 1.375 m, respectively. The blanket design builds upon what has been accomplished in ARIES-AT.[11] The design relies on the inboard (IB) and outboard (OB) blankets to breed the T needed for plasma operation. The OB blanket is divided into two segments with a replaceable inner segment and permanent outer segment. Advanced ARIES physics mandates placing two stabilizing shells close to the FW to enhance several physics parameters (such as beta, elongation, etc.). A favorable location for the OB shells is within the 5 cm wide gap that separates the OB blanket segments.[12]

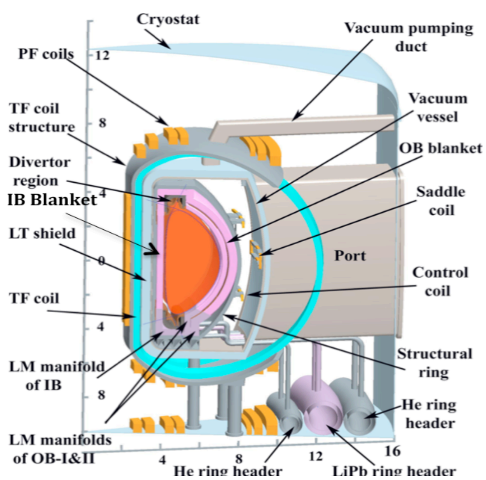

Fig. 1. Isometric view of ARIES-ACT-1 [courtesy of X. Wang (UCSD)].

In the 3-D TBR model, homogenization was avoided except in the 2-3 cm thick FW, side/top/back walls, and cooling channels within the blanket. The fine structures within these components will not affect the breeding. The vacuum vessel and magnets shown in Fig. 1 were not included in the model since their impact on the TBR is insignificant. The starting ^{6}Li enrichment is 90% as in ARIES-AT as well as in past fusion studies employing LiPb as a breeder. Only in the recent ARIES-CS study[5] has the design point been shifted to 70% enrichment in order to provide as extra margin to increase the TBR online, if needed. Thus, the variation in TBR as a function of ^{6}Li enrichment has been assessed for ARIES-ACT.

There are 16 modules toroidally separated by 2 cm wide assembly gaps. Each of the 16 blanket modules spans 22.5^{o} toroidal angle. The upper half of an 11.25^{o} wedge of the tokamak was modeled in the TBR analysis, representing one quarter of the blanket module and $1/64^{th}$ of the entire tokamak. Three reflecting boundaries were placed at both sides of the 11.25^{o} wedge as well as at the midplane. The neutron source distribution within the plasma is adequately presented by three nested regions with varying intensities (63%, 32%, and 5%).[13]

We made good use of the DAGMC code and the stepwise approach. We assessed the degradation in TBR attributed to eight individual design elements that belong to the SiC/LiPb blanket and its external components (7.7 cm thick W-based divertor and He-cooled ferritic steel-based shield). The design elements include the FW, side/top/back walls, cooling channels, W stabilizing shells, assembly gaps, and penetrations. Special care has been taken to model all details to reflect the exact design specifications of the blanket. The stepwise approach enabled step-by-step addition of the individual elements to the blanket envelope and records the corresponding incremental change to the TBR. For a precise representation, the individual blanket elements were first modeled by the CAD system, and then coupled with the MCNP code through DAGMC. This unique capability allows a fully accurate representation of the blanket geometry with high fidelity in the 3-D TBR results.

III. THE 3-D TBR RESULTS

The bottom-line results are displayed in Fig. 2 for the reference LiPb eutectic that contains 15.7 at% Li and 84.3 at% Pb.[14] This bar chart represents the calculated TBR from a series of eight 3-D runs performed to illustrate the stepwise degradation in breeding by various elements of blanket internals and surroundings. The eight individual steps are discussed below along with the detailed change(s) made to the 3-D models for each step.

Step 1: To estimate the highest achievable TBR for any LiPb system, a model of an infinite cylinder was created with 2 m LiPb with 90% ^{6}Li enrichment and no structure followed by 2 m thick ferritic steel (FS) shield to provide the appropriate neutron reflection that enhances the breeding. The corresponding TBR for this ideal configuration is 1.79, marking the first bar in Fig. 2.

Step 2: The toroidal model was constructed using ARIES-ACT-1 major and minor radii. In this initial model shown in Fig. 3, the 35 cm IB and the 75 cm OB breeding zones are well-defined radially and poloidally and surrounded with the shield and divertor. The D-shape plasma contains the three nested neutron source regions. The two OB blanket segments are separated by a 5 cm wide gap to accommodate the stabilizing shells. The 3-D configuration with such a limited blanket thickness and poloidal coverage dropped the TBR by ~22%.

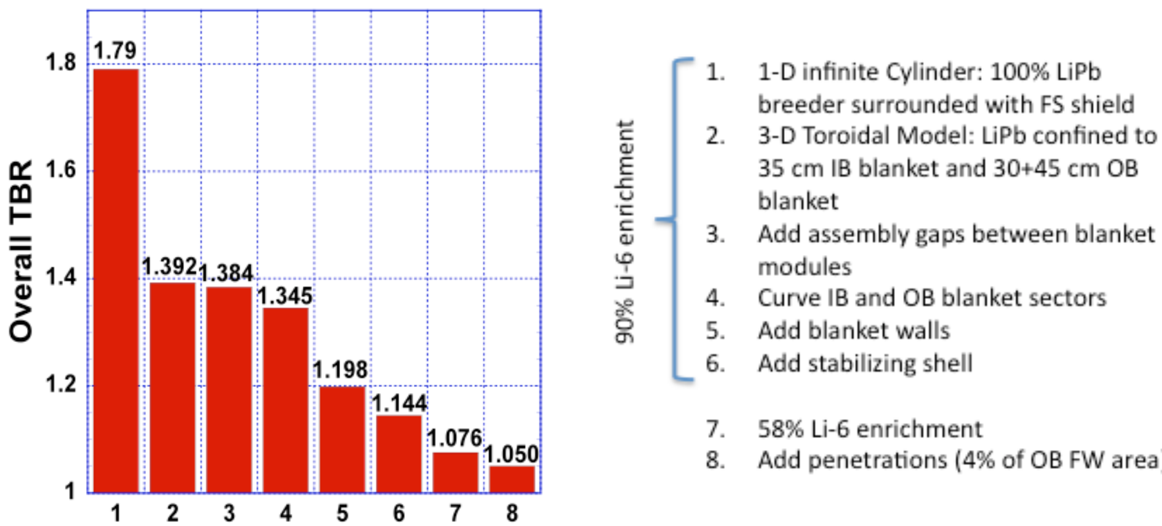

Fig. 2. Bar chart showing reduction in TBR upon including the blanket internals and externals.

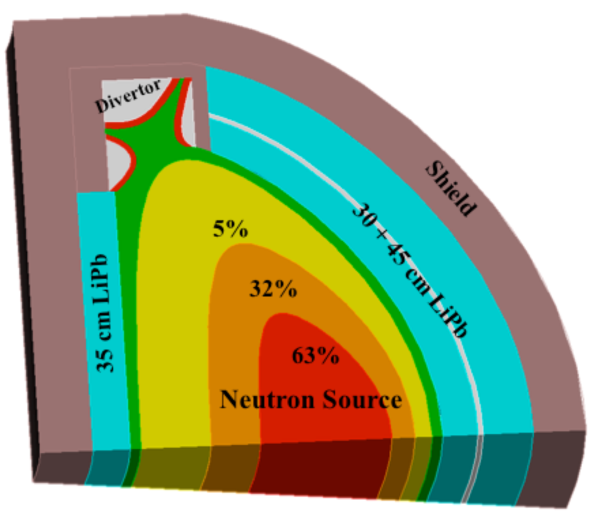

Fig. 3. 3-D model of ARIES-ACT-1 where the breeder is limited to 35 cm on the inboard and 75 cm on the outboard.

Step 3: There is a 2 cm wide assembly gap between adjacent modules to allow for thermal expansion, neutron-induced swelling, and radial removal of modules during maintenance. Since half of the blanket module is being considered, the gap in the 3-D model is 1 cm wide and was modeled on one side of the 11.25^o wedge. The TBR degraded slightly (0.6 %) due to the addition of the gap.

Step 4: The IB and OB blankets are segmented into sectors. The front and back are curved for each sector,[10] keeping the maximum blanket thickness fixed. The shaping of the blanket dropped the TBR by 3%.

Step 5: SiC structure with ~50% LiPb coolant is assigned to the IB and OB first/side/back/top walls at the perimeter of the blankets and cooling channels between sectors as shown in Fig. 4. The SiC structure caused the TBR to drop by ~ 11%.

Step 6: There are two stabilizing shells located between the OB blanket segments. The 1 cm thick W Kink shell spans the module from the midplane to 45^o while the 4 cm thick Vertical shell is located between 55^o-85^o as shown in Fig. 5 for the final 3-D model. The impact of both shells is a 4.5% drop in TBR.

Step 7: The ^{6}Li enrichment was varied to determine the possibility of operating ARIES-ACT at lower enrichment than 90%. Figure 6 suggests an enrichment of 58% to satisfy the 1.05 TBR requirement. The 2-3% excess margin accounts for the effect of penetrations (see Step 8 below). Lowering the enrichment from 90% to 58% degrades the TBR by 6%.

Step 8: The heating and current drive (H&CD) penetrations occupy ~4 m^2 of the OB FW area. There are ~20 small fueling ducts with ~4 cm^2 each. Diagnostics may add another 3 m^2 (Ref. 15), totaling 7 m^2 for the penetration footprint at the OB FW. This represents ~2% of the OB FW area. However, we doubled this area to account for less advanced H&CD technologies with a heating limit of 10 MW/m^2 at the orifice. Assuming a direct correspondence between the area of penetrations and the reduction in OB breeding, we would expect the TBR to drop by 2.4% if all penetrations occupy 4% (12 m^2) of the OB FW area. When the location, orientation, and configuration of penetrations and diagnostics are better defined, future 3-D models will evaluate more precisely their effect on TBR.

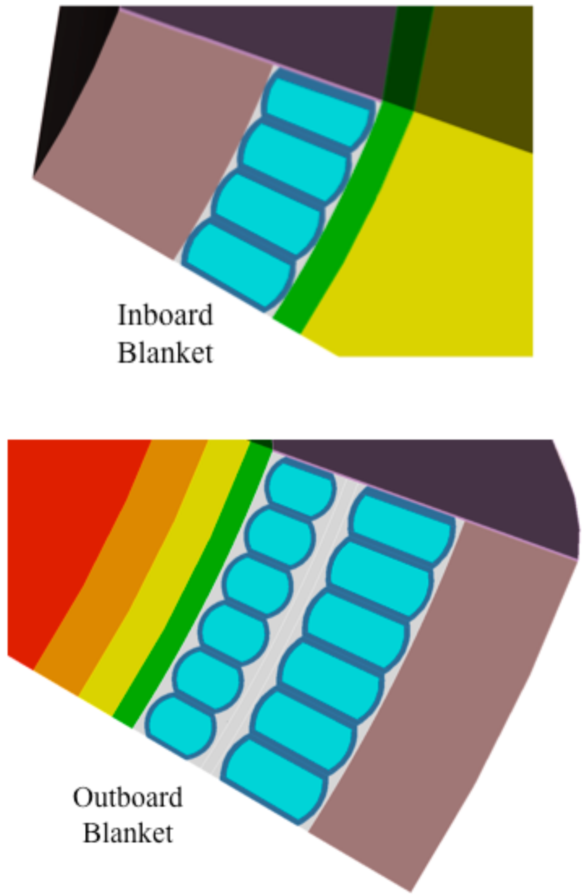

Fig. 4. SiC structure of FW and side/back walls, and radial cooling channels added to the 3-D model.

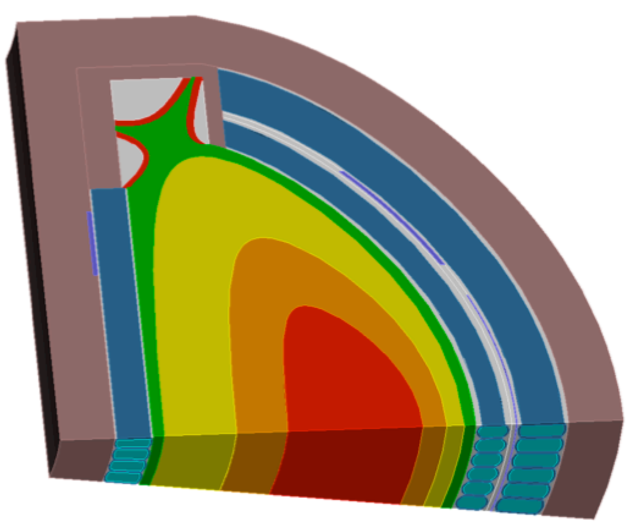

Fig. 5. Isometric of ARIES-ACT-1 showing cross section of IB and OB blankets at the midplane.

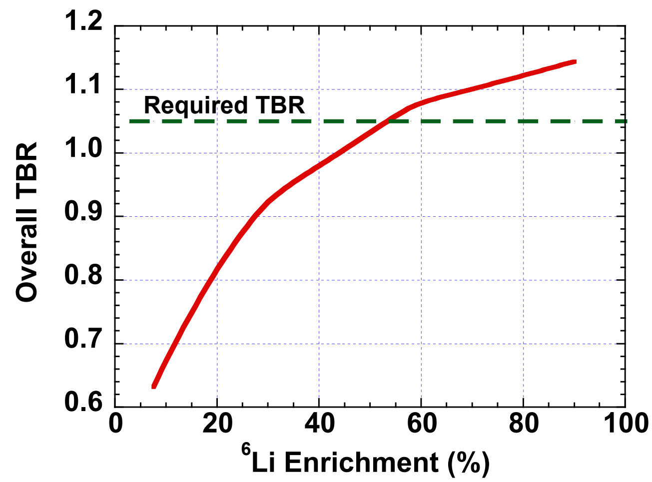

Fig. 6. Sensitivity of TBR to ^{6}Li enrichment.

IV. GENERAL REMARKS AND CONCLUSIONS

We applied a state-of-the-art TBR assessment to the latest tokamak project being undertaken in the US by the ARIES team. Our analysis attempted to answer many design-related breeding questions and showed the progressive reduction of the theoretical TBR (~1.8) down to the more realistic TBR (1.05) when the real geometry of the SiC/LiPb blanket is addressed. We made extensive use of the most advanced calculation tools (the newly developed DAGMC code that couples the CAD design to the 3-D neutronics code) in order to model all engineering details of the blanket. To fully understand the importance of each design refinement on the TBR, we added "step-by-step" the various blanket components (e.g. SiC walls, cooling channels stabilizing shells, assembly gaps, penetrations, etc.) and evaluated the impact of each component on the TBR. Our findings not only confirm the ARIES-ACT-1 blanket complies with the ARIES breeding requirements (calculated TBR of 1.05 with ~60% ^{6}Li enrichment), but also provide a rational basis for the damaging and enhancing changes to the breeding of several blanket design elements:

- Limiting the blanket coverage radially and vertically has the largest impact on TBR (22%)
- Shaping the blanket and adding the SiC structure have a 14% reduction in TBR
- Inclusion of stabilizing shells has ~5% impact on TBR
- Adding penetrations and assembly gaps has smaller (3%) but still significant impact on TBR.

Despite the great interest in understanding how these elements impact the breeding in an integral fashion, an important question remained unanswered: will the ARIES-ACT-1 blanket over-breed or under-breed during plant operation? Because many uncertainties in the operating system govern the achievable breeding level, the Net TBR (around 1.01) will not be verified until after the operation of a Demo with fully integrated blanket, T extraction system, and T processing system. Thus, it is a must requirement for any blanket design to have a flexible approach that helps deal with the shortage or surplus of tritium obtained as a consequence of the actual operational life. The most attractive scheme for a LiPb breeder in particular is to increase/decrease the ^{6}Li enrichment online shortly after plant operation. This scheme helps mitigate concerns about the danger of placing the plant at risk due to tritium shortage as well as the problem of handling and safeguarding any surplus of tritium.

ACKNOWLEDGMENT

This work was performed under the auspices of the US Department of Energy under contract #DE-FG02-98ER 54462.

REFERENCES

1. L. EL-GUEBALY and S. MALANG, "Toward the Ultimate Goal of Tritium Self-Sufficiency: Technical Issues and Requirements Imposed on ARIES Advanced Fusion Power Plants," *Fusion Engineering and Design*, **84**, 2072 (2009).
2. F. NAJMABADI et al., "Re-examination of Visions for Tokamak Power Plants: ARIES-ACT Study," *these proceedings.*
3. X-5 MONTE CARLO TEAM, "MCNP–A General Monte Carlo N-Particle Transport Code, Version 5." Volume I: Overview and Theory, LA-UR-03-1987; Volume II: User's Guide, LA-CP-03-0245; Volume III: Developer's Guide, LA-CP-03-0284, Los Alamos National Laboratory (October 2005).
4. M. WANG, D. HENDERSON, T. TAUTGES, L. EL-GUEBALY, and X. WANG, "Three - Dimensional Modeling of Complex Fusion Devices Using CAD-MCNP Interface," *Fusion Science and Technology*, **47**, No. 4, 1079 (2005).
5. L. EL-GUEBALY, P. WILSON, D. HENDERSON, M. SAWAN, G. SVIATOSLAVSKY, T. TAUTGES et al., "Designing ARIES-CS Compact Radial Build and Nuclear System: Neutronics, Shielding, and Activation," *Fusion Science and Technology*, **54**, No. 3, 747-770 (2008).
6. M. E. SAWAN, P. P. H. WILSON, T. TAUTGES, L. A. EL-GUEBALY, D. L. HENDERSON, T. D. BOHM, E. P. MARRIOTT, B. KIEDROWSKI, B. SMITH, A. IBRAHIM, and R. SLAYBAUGH, "Application of CAD-Neutronics Coupling to Geometrically Complex Fusion Systems." Proceedings of 23rd IEEE/NPSS Symposium on Fusion Engineering (SOFE), May 31-June 5, 2009, San Diego, CA, ISBN No. 978-1-4244-2636-2, IEEE Cat. No. CFP09SOF-CDR. Available at: http://fti.neep.wisc.edu/pdf/fdm1363.pdf.
7. "DAGMC Users Guide," University of Wisconsin-Madison Fusion Technology Institute (2008). Available at: http://cnerg.engr.wisc.edu/cgi-bin/index.cgi/wiki?p=DagmcUsersGuide.
8. L. EL-GUEBALY, A. JABER, and S. MALANG, "State-of-the-Art 3-D Assessment of Elements Degrading the TBR of the ARIES DCLL Blanket," *Fusion Science and Technology*, **61**, #4 321-331 (2012).
9. L. A. EL-GUEBALY and S. MALANG, "Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants," University of Wisconsin Fusion Technology Institute Report, UWFDM-1372 (2009). Available at: http://fti.neep.wisc.edu/pdf/fdm1372.pdf.
10. M. S. TILLACK, X. R. WANG, S. MALANG, and F. NAJMABADI, "ARIES-ACT-1 Power Core Engineering," *these proceedings.*
11. L. A. EL-GUEBALY, "Nuclear Performance Assessment of ARIES-AT," *Fusion Engineering and Design*, **80**, 99-110 (2006).
12. L. MYNSBERGE, A. JABER, and L. EL-GUEBALY, "Three-Dimensional Evaluation of Tritium Breeding Ratio, Nuclear Heating Distribution, and Neutron Wall Loading Profile for ARIES-ACT LiPb/SiC Design," University of Wisconsin Fusion Technology Institute Report, UWFDM-1414 (2012). Available at: http://fti.neep.wisc.edu/pdf/fdm1414.pdf.
13. R. N. SLAYBAUGH, P. P. H. WILSON, L. A. EL-GUEBALY, and E. P. MARRIOTT, "Three-Dimensional Source Models for Toroidal Fusion Energy Systems," *Fusion Engineering and Design*, **84**, Issues 7-11, 1774 (2009).
14. P. HUBBERSTEY, T. SAMPLE, and M. BARKER, "Is Pb-17Li Really the Eutectic Alloy? A Redetermination of the Lead-Rich Section of the Pb-Li Phase Diagram ($0.0 < x_{Li}$(at%) < 22.1)," *Journal of Nuclear Materials*, **191-194**, 283 (1992).
15. K. M. YOUNG, "An Assessment of the Penetrations in the First Wall Required for Plasma Measurements for Control of an Advanced Tokamak Plasma Demo," *Fusion Science and Technology*, **57**, 298 (2010).