Impact of Tritium Breeding on Design Implications to Withstand Disruptions and Runaway Electrons

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Scope and Motivation: During off-normal events, the thermal energy deposition will result in a loss of first wall armor due to evaporation and/or melting. The first wall (FW) of ARIES fusion power plants can tolerate a few off-normal events (disruptions, runaway electrons, ELMs, and VDEs). Frequent off-normal events call for a thick armor that tends to degrade the tritium breeding considerably. At present, practical means to enhance the breeding while accommodating frequent off-normal events do not exist for the ARIES DCLL blanket concept (that employs ferritic steel (FS) structure and dual coolant: He and lithium lead). There is a definite need to actively control such off-normal events for Demo and future power plants.

Thermal Effects of Disruptions, ELMs, and VDEs
Plasma thermal effects on plasma facing components (PFC) are important for all blanket concepts. However, electromagnetic effects inducing stresses in the structure are especially important for power plants with conducting walls (e.g., the DCLL concept).

Based on the thermal energy deposition and the corresponding loss of armor (due to evaporation and/or melt layer loss), only a few events can be tolerated within the expected lifetime of the FS-based FW (3-4 FPY) of ARIES power plants [1,2]:

- For a disruption energy density of 28-45 MJ/m^2 over 1-3 ms, which is at least four times as high as ITER's, only a few disruptions can be tolerated.
- ELMs, in a thermal quench mode, deposit ion energies of 0.77 or 3.8 MJ/m^2 in controlled or uncontrolled modes, respectively. ELMs may occur frequently and with 10-100 events will result in a not-acceptable evaporation loss of FW material. A limited number of ELMs can be tolerated (depending on the energy density). Tungsten armor could accommodate the ELMs better than a SiC armor or a bare FS FW.
- ITER-type VDEs could deposit up to 60 MJ/m^2 in 0.2 sec. Not even one VDE can be accommodated based on such severe VDE parameters.
- For more advanced blanket concepts with resistive walls (e.g., with SiC/SiC structure), the thermal effect is less severe.

The ARIES team has not performed a thorough structural analysis based on disruption loads for the most recent ARIES tokamak designs, similar to that of ITER by D. Williamson. Such structural analysis would apply to both DCLL FS-based design and ARIES-AT SiC/SiC-based design [3]. The low electrical conductivity of SiC might help reduce the disruption loads. Once a scenario for a few disruptions allowed in Demo is better characterized, such a structural analysis should be done.

Impact of Thick FW Armor on Tritium Breeding
Here, we describe the impact of the off-normal event requirements (in terms of the need to add a fairly thick armor on the FW) on the overall machine design to enable an adequate tritium breeding ratio (TBR). In latest ARIES designs developed over past 10 years, we only consider blankets with LiPb as a breeder with no need to use an additional multiplier such as Be.

Background info: The overall TBR depends on the blanket composition, thickness, coverage, and ^{6}Li enrichment. We design the blanket for tritium self-sufficiency with a calculated overall TBR of 1.1 to account for uncertainties and other design requirements [4]. The latest trend in blanket design is to satisfy the breeding requirement with < 90% ^{6}Li enrichment. This allows the use of the ^{6}Li enrichment as a knob to control the tritium breeding level during operation (i.e., to breed slightly more/less tritium as needed) [5].

How much excess breeding margin is available? The ongoing ARIES-AT-DCLL study (that combines the advanced physics of ARIES-AT [3] with the DCLL blanket system) indicated a marginal breeding even without including the stabilizing shells and despite an effort made to enhance the breeding through the use of thin SiC inserts [6]. Figure 1 displays the impact of the FW thickness on the local breeding of the DCLL blanket. Thickening the DCLL blanket to compensate for the breeding losses will not help much as the breeding levels off at 70-80 cm (refer to the right plot). Note that this local TBR does not take into consideration the blanket coverage, penetrations, or non-uniformity in blanket thickness (e.g., inboard vs. outboard). For an equivalent FS of 1.3 cm in the 3.8 cm thick FW, the overall TBR approaches 1.1 with 70% ^{6}Li enrichment [6]. This overall TBR takes into account all the items mentioned above.

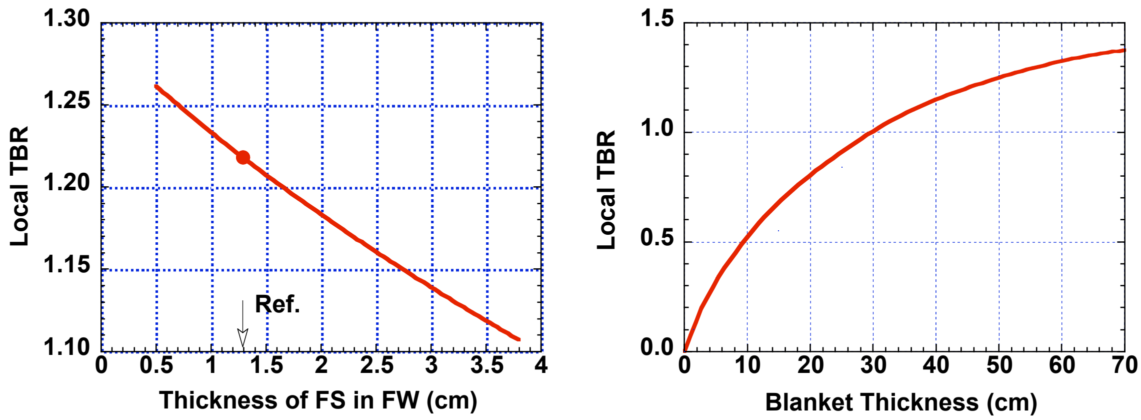

Figure 1. Sensitivity of local TBR to FW and blanket thicknesses [4].

How could ARIES designs deal with any additional structural requirements for off-normal events? The answer depends on where this additional structural material is localized. Since the breeding peaks around the midplane, adding a few mm of materials to the upper/lower ends of the FW could be acceptable. If the material should be added uniformly over the entire FW of ARIES-AT-DCLL, one or two mm could be accommodated with further optimization of the blanket configuration.

Breeding capacity

Different blanket concepts have different breeding capacity. Solid breeder and Flibe blankets containing beryllium (as an essential multiplier to achieve T self-sufficiency) tend to have a larger breeding margin than LiPb blankets. Adding Be to the ARIES-AT-DCLL blanket may enhance the breeding capacity. However, Be will degrade the safety rating of the DCLL blanket. Be is a toxic material and has been declared a carcinogen if inhaled [7]. Recent ARIES designs made a serious effort to avoid using Be in the blanket. This position is not universal as European and Japanese employ Be in their solid breeder blankets.

How much above an overall TBR of 1.1 could we get by adding Be to the LiPb blanket? We don't have a quantitative answer for the DCLL blanket as we never looked at this case before. However, in the 1980s, UW developed a thin LiPb/Be/He/FS blanket for MINIMARS – a tandem mirror power plant. Reference 8 shows the peaking in breeding with Be. We're not sure if the MINIMARS blanket design is still valid based on the most recent Be data. The breeding level may degrade if we reevaluate this design with the most recent cross section library.

Summary

The following points can be made:

- There is no practical means to enhance the breeding of the DCLL blanket if the off-normal events require adding more than 1-2 mm FS on the FW.
- There is a sufficient design space for the occasional once per year disruption and a few ElMs, but no VDEs.
- Disruption, ELMs, and VDEs avoidance and/or mitigation scheme is a necessity for Demo and future power plants.
- It is highly desirable to avoid using Be in ARIES blankets as it introduces many safety concerns.
- Advanced SiC/SiC composites offer interesting concept, but the time to develop and qualify them could be considerable.

References

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