

**SNOWMASS HOT TOPIC
CHAMBER SCIENCE AND TECHNOLOGY
KEY QUESTION NUMBER 5**

***CORE WORKING GROUP OPINION PAPER
RE-EVALUATION OF THE USE OF LOW ACTIVATION MATERIALS IN
WASTE MANAGEMENT STRATEGIES FOR FUSION***

Background

Materials choice has long been recognized as a key factor in realizing the full safety and environmental potential of fusion power. Because the materials are de-coupled from the fusion energy source (the plasma), the long-term neutron-induced activation of components can be tailored by proper selection of materials to avoid generation of waste that would require deep geological disposal. Thus, the idea of “low activation” materials was conceived for the US fusion program with the hope that such material could be disposed of as low level waste (e.g., shallow land burial) and would not pose a burden to future generations.

The environmental impact of waste material is, however, determined not only by the level of activation, but also the total volume of active material. A tokamak power plant is large, and there is a potential to generate a correspondingly large volume of activated material. The adoption of low activation materials, while important to reduce the radiotoxicity of the most active components, should be done as part of a strategy that also minimizes the volume of waste material that might be categorized as radioactive, even if low level. Waste management strategies have typically concentrated on minimizing the activity of first wall and blanket components where the level of specific activity (Bq/kg) is highest [1].

Some materials may become candidates for recycling, and others may be cleared from regulatory control by meeting prescribed criteria that have yet to be agreed upon internationally. Recently these concepts of recycling or clearance have been recognized as options for reducing the volume of radioactive waste from a fusion power plant. Determining if a material can be recycled or cleared from regulatory control depends largely on our ability to limit the induced activation of the component. (It should be noted that the criteria for clearance are more restrictive than for recycling.) Thus, there is a need to explore new and innovative concepts that can substantially reduce the activation of the large ex-vessel components that contribute significantly to the overall volume of activated material and to extend the capability of conventional conceptual fusion designs with proper optimization to achieve the same goal. The impact of these parameters on other aspects of plant performance must also be considered.

In this hot topic, we review scoping studies with neutronics and activation models to examine these issues, and identify the trends which allow improved in-vessel shielding to result in reduced ex-vessel activation. The performance of typical fusion power plant designs with respect to recycling and clearance criteria are also assessed, to show the potential for improvement in waste volume reduction by careful selection of materials combinations. The implications of the results on the development path for fusion power are discussed.

Scoping Study

A scoping study has been performed to examine a broad range of blanket design concepts in Europe and the US with fixed plasma and ex-vessel components and determine their ability to minimize ex-vessel activation. [2] Most of these blanket options are based on the tokamak power plant designs studied in the European Safety and Environmental Assessments of Fusion Power (SEAFP), in particular the three models adopted in the second phase of that study. These were augmented by a lithium metal/vanadium concept based on work in the US and a silicon carbide variant of one of the SEAFP blankets.

The five different design options are:

- (a) Lithium oxide ceramic breeder/vanadium alloy structure/helium coolant
- (b) Liquid LiPb breeder/low activation martensitic (LAM) steel structure/water coolant
- (c) Lithium silicate ceramic breeder/ LAM steel structure/helium coolant
- (d) Lithium silicate ceramic breeder/silicon carbide composite structure/helium coolant
- (e) Self-cooled lithium breeder/vanadium alloy structure

In all cases except the lithium/V design, water-cooled austenitic steel (containing a full set of elements and impurities) is used for the shield and vacuum vessel. For the lithium/V design, because of the safety concern related to lithium/water interaction, the shield and vacuum vessel are helium-cooled austenitic steel. Beyond the vacuum vessel is the superconducting magnet winding pack with the associated insulation enclosed in its austenitic steel coil case.

Although such designs options may not be fully optimized, the use of constant ex-vessel components allows us to understand the degree of ex-vessel activation as a function of the low activation materials combinations in the FW/blanket and further helps us understand the underlying trends. (In fact, in an optimized design, different shields might be used to compensate for the shielding effectiveness of different blankets.) To compare the ex-vessel activation of the different options, we use a clearance index based on IAEA recommendations [3] regarding levels of activation below which a material is no longer classified as radioactive waste.^a

Figure 1 plots the clearance index in each component after 50 years of decay. The activation response of the different plant models in Figure 1 shows that the use of different low activation material/coolant combinations in the blanket produces very different levels of activation in the shield, vacuum vessel and magnets. It is clear that optimizing the breeder, structure and coolant materials within the first wall and blanket to reduce the activation response in these regions, results in a higher activation in the shield, vacuum vessel and magnets. The converse is also true, as seen by comparing the behavior of ceramic/SiC/He with that of LiPb/LAM/water.

Further, the level of induced activation of the vacuum vessel as given by the clearance index varies by a factor of 500 among the different design options. The combination of water, LiPb and low activation martensitic steel in the blanket provides superior shielding of all the blankets considered from an ex-vessel neutron activation standpoint. The shielding offered by the Pb and the moderation of the water results in the lowest clearance index (and although not shown, the lowest specific activity and dose rate) in the shield and vacuum vessel of all the designs considered.

Vacuum vessel/ex-vessel activation is primarily a function of the choice of low activation structural material in first wall and blanket and the neutron moderating effectiveness of blanket coolant fluid, as

^a Clearance index is defined in the same manner as the US waste disposal rating as the ratio of the specific activity of a nuclide divided by the clearance limit summed over all isotopes

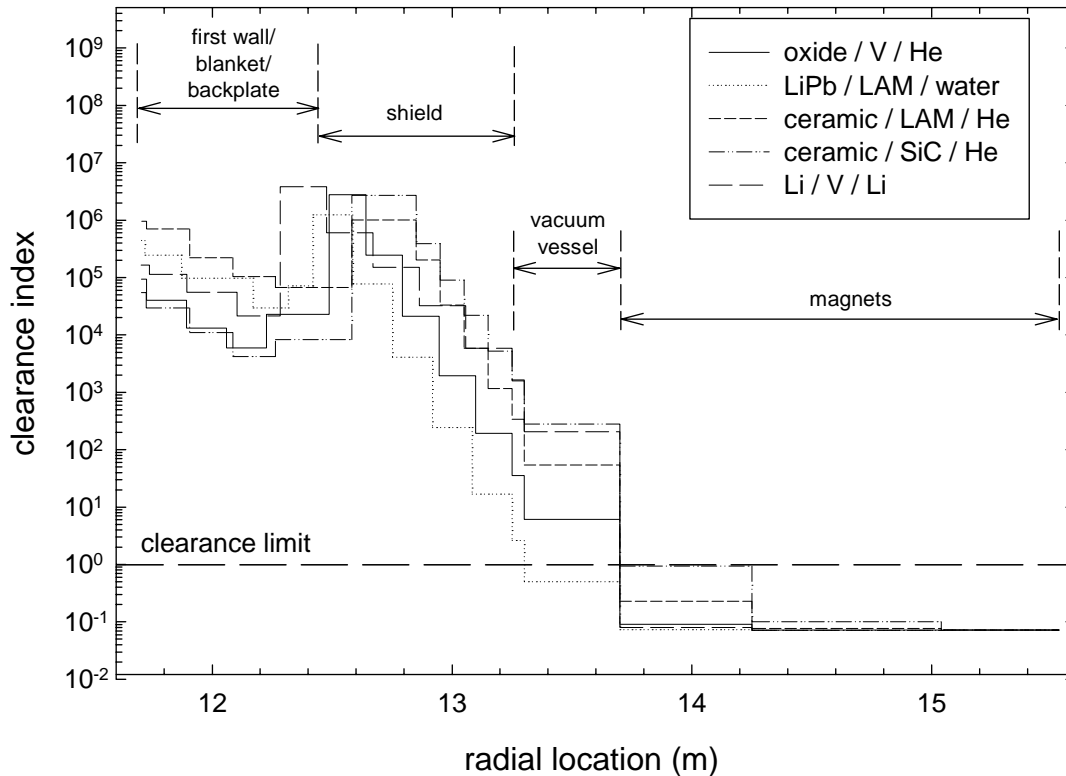


Figure 1 Clearance Index for Different Design Options

ARIES RS Design

The scoping study was useful to understand the trends offered by different low activation material combinations. It is however useful to examine the more optimized ARIES-RS design to determine the degree to which ex-vessel activation can be reduced by more careful design of the shield. The ARIES-RS design has a Li/V blanket and specially optimized shields for both the inboard and outboard portions of the machine. Both inboard and outboard regions contain a vanadium alloy/tenelon high-temperature shield. The inboard low temperature shield is WC and Tenelon. (Tenelon is a low activation austenitic steel). The outboard low temperature shield is a mixture of borated Tenelon and Tenelon.

In Table 1, we compare the clearance index for the vacuum vessel for the Li/V design in the scoping study, the ARIES-RS design, and a modified ARIES-RS design in which the vacuum vessel is changed to a low activation ferritic steel (LAFS). (It should be noted that changing to LAFS may

result in not meeting the magnet insulator dose limit. Thus, the design would have to be optimized. The change in materials here is just to illustrate the effect on clearance.) Changing the VV material from 316 SS to Tenelon, a reduced activation austenitic steel reduced the clearance index (and hence ex-vessel activation) of the vacuum vessel significantly (from a clearance index of 1600 to 6), largely because of the reduction in the Co concentration of the two steels. Going from Tenelon to LAFS does not change the clearance level significantly.

Table 1. Effect of shielding and VV material on the clearance Index for different Li/V options.

	Li/V design option from scoping study with 316 SS VV	ARIES-RS with Tenlon VV	ARIES-RS with low activation ferritic steel VV
Inboard VV	---	5.7	5.6
Outboard VV	1600	1.6	1.5

High Power Density/High Wall Load Designs

As part of examining this overall question or reduced ex-vessel activation, it is useful to also consider what role the new high power density/high wall load designs being considered in the Advanced Power Extraction (APEX) study may have on reducing ex-vessel activation. The higher wall loads accessible by liquid walls, and the use of refractory alloys (e.g tungsten) with superior shielding capabilities relative to steel could lessen the ex-vessel activation. We examine these two issues below:

For a given power output, the higher wall load afforded by a thick liquid first wall and blanket can reduce the volume of waste from the first wall and blanket significantly because of the reduction in size of the FW/blanket, the lower structural content of thick liquid wall designs, and the potential for increased lifetime of a liquid blanket. An illustrative example follows in the Table 1 below.

Table 2 Rough order of magnitude comparison of FW/blanket waste volumes for different concepts

Concept type	Peak Wall Load MW/m ²	FW/Blanket Structure Fraction	Approximate FW/Blanket Lifetime	Reduction in waste volume of FW and blanket components for liquid wall high power density designs relative to solid walls
Low wall load commercial reactor	1	10-20%	15 FPY	50-100
ARIES-RS	5.5	10%	2.5 FPY	
Liquid walls*	10	--	30 FPY	

The 300 MWyr/m² lifetime of the structure behind the liquid walls is based on calculations for Flibe as the liquid. Other liquids would have lower lifetimes.

The results show that liquid walls reduce the volume of FW/blanket waste by a factor of 50 to 100. It should be noted that some might argue higher values based on more pessimistic estimates of lifetimes of conventional solid walls. At the same time, others have argued that if solid first walls and blankets can be recycled and reused then that material is no longer waste and thus the waste volume difference might be somewhat lower. (It is important to note that we have not examined the waste streams from the breeding material in these comparison. For the liquids, we would have to examine the waste stream from Li, Flibe, LiPb, or LiSn and for solids it is important to examine the waste streams from the solid breeder (e.g., lithium zirconate, silicate, titanate or aluminate) and the Be neutron multiplier.)

In addition to a reduction in the FW/blanket waste volume, higher power density designs result in a more compact machine which reduces the volume of the shield, vacuum vessel and magnet components. Figure 2 plots the volume of these components as a function of wall load. Comparison of volume of these components at the 10 MW/m² value with the volume at the ARIES-RS value of 4 MW/m² shows a reduction in overall volume of these components by about a factor of 2. This is a significant reduction!

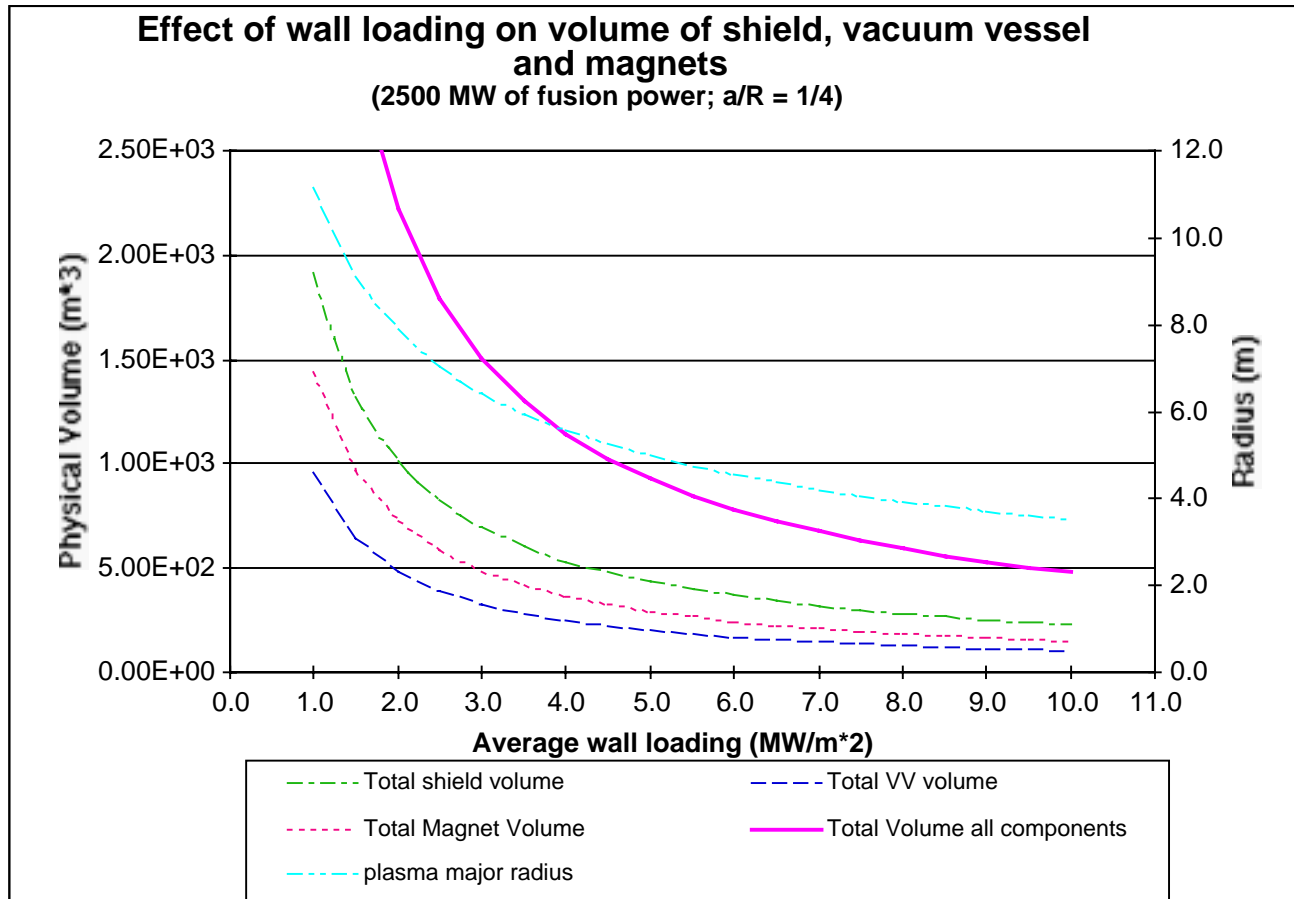


Figure 2

Finally, we examine the effect of using refractory alloys in the first wall and blanket with their superior shielding capabilities relative to steel on the ex-vessel activation characteristics in some of the APEX designs. All of the APEX designs use a LAFS vacuum vessel. Thus, Figure 3 compares the clearance indices of different APEX designs to the baseline ARIES-RS design with a LAFS VV. The results show the higher activation afforded by the TZM alloy in the FW and blanket. Comparison of the clearance index in the VV of the different designs show that the clearance index of the VV in all of the APEX designs is higher than in ARIES-RS. Clearly, the APEX designs are at a very conceptual stage and have not had the degree of optimization as had ARIES-RS.

From a safety and environmental perspective, the use of such refractories offers challenges with regard to high decay heat and short term activation. However, the superior shielding effectiveness of these materials should in principle improve the ex-vessel activation situation described here. We recommend that these APEX designs take better advantage of the superior shielding performance of the refractory alloys like tungsten by further optimization of the shield to reduce ex-vessel activation. This approach would establish an environmental benefit for the use of tungsten to offset the high short term decay heat and activation that are safety concerns associated with these materials. (It

would still be necessary to ensure that all designs provide adequate radiological confinement and afterheat removal to ensure that safety limits are met.

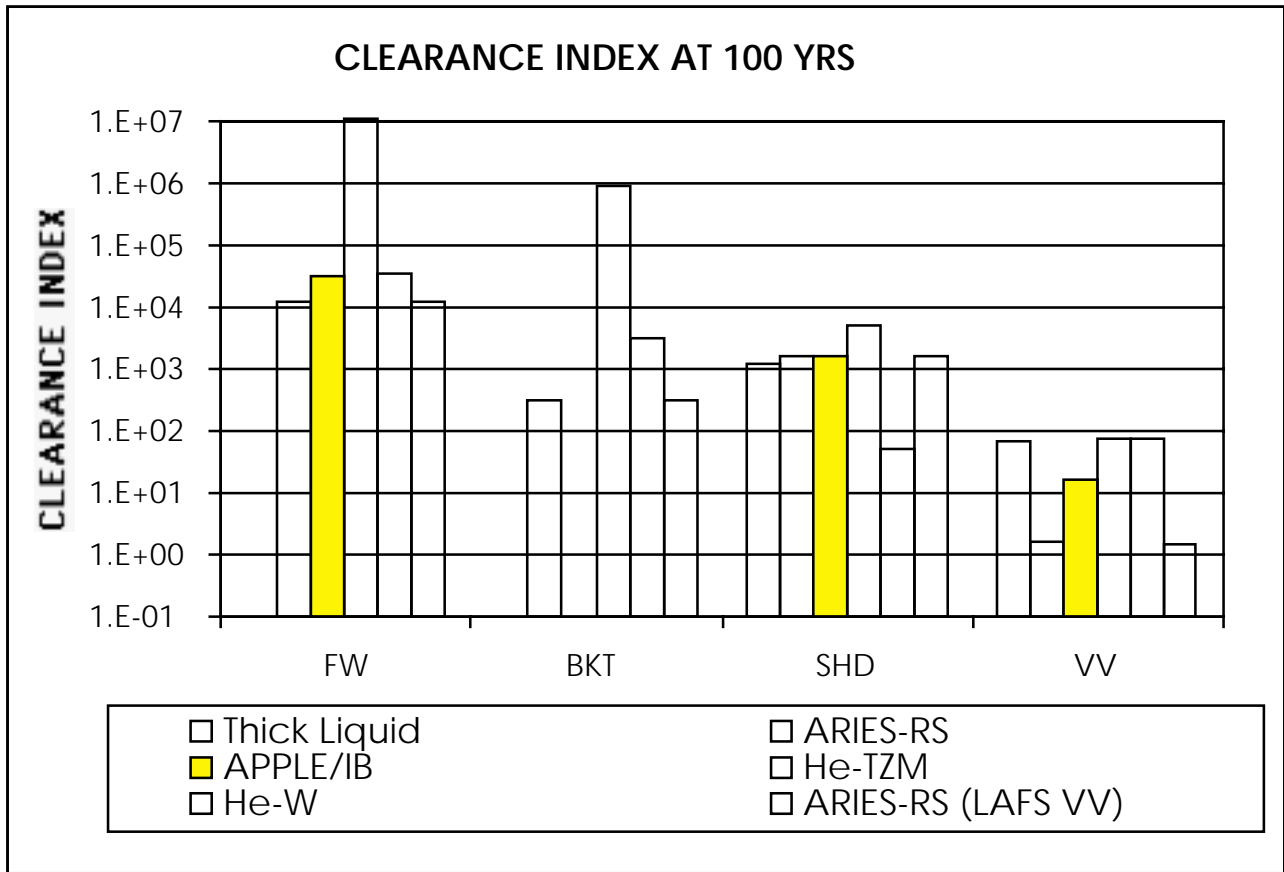


Figure 3. Clearance index for different APEX design concepts

Summary

These results have begun to examine the effect of shielding and materials choice on ex-vessel activation. They suggest that the waste management strategy for fusion needs to be modified slightly. While low activation materials do reduce the long-term activation hazard of the waste, their use in and of itself does not necessarily reduce the volume of activated material and the subsequent amount of radioactive waste arising from the plant. As has been shown previously, [4,5,6,7] the development of low activation materials to reduce the in-vessel radiotoxicity hazard requires careful attention to impurities in the materials used in the near plasma components. While impurities are still important, the reduction of vacuum vessel/ex-vessel activation to levels that would allow the vacuum vessel and magnets to be cleared requires a combination of optimized bulk shielding by the blanket and shield, the use of reduced-activation steel in the vacuum vessel and ex-vessel components.

A waste management strategy focused solely on low activation materials does not address the entirety of the radioactive waste picture for fusion. We recommend a strategy that is balanced with respect to minimizing both the hazard (via low activation materials) and the volume (via reduction of ex-vessel activation). As such we propose the following minimum design goals:

- To reduce the overall radioactive waste volume by limiting vessel/ex-vessel activation so that the outboard vacuum vessel and all magnet components be cleared using IAEA clearance rules or recycled for re-use.

- To ensure that all activated material in a fusion plant that cannot be cleared or recycled be disposed of as low level waste and thus not pose a burden to future generations.

Furthermore, there is also a need to better understand the tradeoffs associated with this dual strategy of minimizing both hazard and volume. For example, some results suggest that some choices of low activation materials for near plasma components suffer the penalty of enhanced neutron penetration, giving rise to higher overall levels of activation, contact dose rate, and clearance index in the shield and ex-vessel components. Materials are considered "low activation" either because their neutron cross sections are low or because their activation products are stable or benign (short-lived), or some combination of these two properties. Those which are merely low absorption may result in higher overall plant activated material volume. Systems and power plant studies should examine in a systematic manner the tradeoffs associated with changing blanket and shield materials to meet these new design goals relative to changes in the radial build of the machine, cost of energy, performance impacts and reduction of radioactive waste volume.

In addition to their improved performance potential via high wall load and high efficiency, high power density/high wall load concepts offer important advantages relative to the overall volume of activated waste in a fusion machine. Liquid wall concepts with higher wall loads can reduce the volume of FW and blanket structural material wastes by a factor of 50 to 100 relative to conventional solid wall concepts. Furthermore, the higher wall load produces a more compact machine, which in turn reduces the volume of the bulkier activated components (e.g., shield, VV, and magnets) by about a factor of 2. Finally, for those high power density designs that use tungsten, we recommend that they take better advantage of the superior shielding performance of the refractory alloys like tungsten by further optimization of the shield to reduce ex-vessel activation. This approach might establish an environmental benefit for the use of tungsten to offset the high short-term decay heat and activation that are safety concerns associated with these materials. In addition, the impact on overall cost of the machine which uses tungsten needs to be evaluated.

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