INITIAL ACTIVATION ASSESSMENT FOR ARIES COMPACT STELLARATOR POWER PLANT

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As the safety assessment frequently requires knowledge of the activation parameters, we estimated the highest possible activity, decay heat, and waste disposal rating on the time scale after shutdown for the compact stellarator power plant ARIES-CS. We selected two widely different systems employing SiC/SiC composites and low-activation ferritic steel (FS) as structural materials. Our results show that components of both systems qualify as Class C low-level waste (LLW) at the end of a 100 y storage period following the decommissioning of the plant. The SiC blanket, vacuum vessel, and magnet offer very low waste disposal rating to the extent that a Class A LLW seems achievable for these components. On this last point, we discussed the split between the Class A and Class C wastes, emphasizing our motivation to lower the level of ARIES-CS radioactive waste.

I. INTRODUCTION

The ARIES team is moving forward with a new study: the ARIES-CS compact stellarator power plant[1]. It is a pioneer 1000 MW_e design that combines advanced physics and engineering approaches to minimize the major radius and hence the overall size of the machine. The design is compact and generates less radioactive waste compared to the predecessor design[2]. Five blanket/shield systems have been considered[3] (LiPb/SiC, LiPb/FS/He, Li/FS/He, Flibe/FS/Be, and Li₄SiO₄/FS/Be/He) and an effort is underway to select a reference design, integrate the internals (blanket, shield, and vacuum vessel), and develop a credible maintenance scheme that supports high availability of 85% or more.
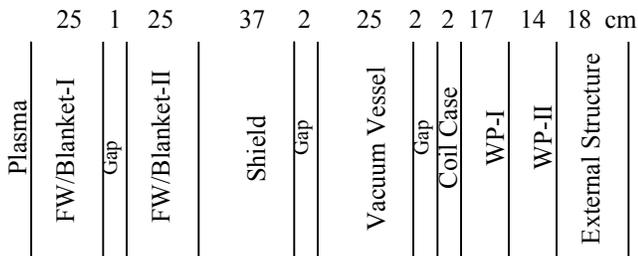
The blanket and divertor cover the majority of the first wall (~90%). At a few localized areas where the magnet moves closer to the plasma, a highly efficient, thinner WC-based shield replaces the blanket to protect the magnet against radiation. We developed two radial builds for each blanket concept: one for the nominal blanket, shield, and vacuum vessel region and the other for the WC-shield and vacuum vessel region[4]. This URL displays the layout of the various radial builds: http://fti.neep.wisc.edu/aries-cs/builds/build.html. We monitored the activation level as the design evolved and called for measures to enhance the safety aspects of the design. We estimated the highest possible activity, decay heat, and waste disposal rating for the two radial builds mentioned above. In the absence of a reference design, we selected two widely different systems (LiPb/SiC and LiPb/FS/He) employing SiC/SiC composites and low-activation ferritic steel (FS) as structural materials.

II. DESIGN DESCRIPTION

The activation results reported herein are based on the analysis performed before April 2004 for an interim design that is subject to change as some engineering and physics issues still need to be resolved. Key design parameters for this initial assessment include an average neutron wall loading of 2 MW/m^2, a first wall/blanket lifetime of 5-6 full power year (FPY), and a permanent component lifetime of 40 FPY. The activation model includes the LiPb blanket, followed by the shield, then the vacuum vessel (VV) and the modular coils. Representative radial builds for the LiPb/SiC and LiPb/FS/He systems are displayed in Figs. 1 and 2.
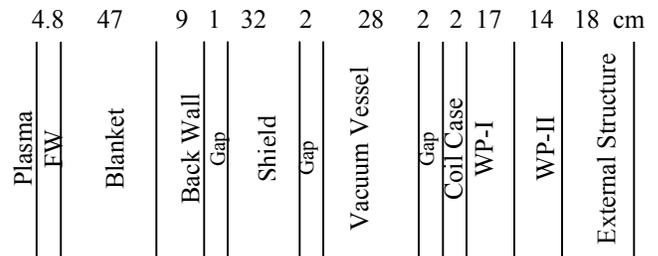

Fig. 1. Schematic of LiPb/SiC radial build.

Fig. 2. Schematic of LiPb/FS/He radial build.

TABLE I. Composition of ARIES-CS Components

Components	SiC System	FS System
FW/Blanket-I (B-I)	21% SiC	6% FS
	79% LiPb	82% LiPb
		12% He
Blanket-II (B-II)	21% SiC	
	79% LiPb	
Back Wall		80% FS
		20% He
Shield	15% SiC	15% FS
	10% LiPb	10% He
	75% B-FS	75% B-FS
Vacuum vessel	28% FS	
	49% H_2O	
	23% B-FS	
Coil case	95% 316-SS	
	5% He	
Winding Pack-I	13% MgB_2	
	45% Cu	
	16% He	
	17% 316-SS	
	9% Polyimide	
Winding Pack-II	9% NbTi	
	54% Cu	
	22% LHe	
	6% 316-SS	
	9% Polyimide	
External structure	95% 316-SS	
	5% He	

Table I identifies the compositions of all components. The impurities of the ODS-MF82H FS structure, SiC/SiC composites, borated FS (3 wt% B) filler, and 316-SS magnet structure have been included in the analysis. The reader is referred to this URL for the alloying elements and impurities of the blanket and shield materials: http://fti.neep.wisc.edu/aries-cs/builds/build.html. The VV and magnet compositions are identical in both cases. The constituents of all components and dimensions meet the ARIES-CS specific design requirements. For instance, 90% enriched LiPb offers an overall tritium breeding ratio of 1.1. All components provide a shielding function. The blanket protects the shield for the entire plant life (40 FPY), both components protect the VV, and all three components protect the high-temperature superconducting magnets. The coil supporting tube surrounds the VV completely. Superimposed on the tube are the grooves for winding the superconductor coils. Figure 3 demonstrates the plasma and 18 winding packs of the three field period design option. A poloidal cylindrical 1-D geometry has been used to model the ARIES-CS system with an average minor radius of 1.85 m. The ALARA activation code[5], DANTSYS transport code[6], and FENDL-2 data library[7] have been used throughout the study. The pulsed history has been represented as 0.85 FPY irradiation time followed by 0.15 FPY downtime, and repeats for 47 y.

The WC shield-only zones cover ~10% of the first wall area[4]. The WC filler replaces the LiPb of the blanket and the borated-FS of the shield, reducing the radial build by ~30 cm. The well-known high decay heat of WC raised some safety concerns. An estimate for the peak temperature at the SiC and FS structures during an accident is currently underway making use of the decay heat as a heat source. If the temperature exceeds the limit of the reusability of the structure, a separate decay heat removal loop will be installed within the WC-shield in particular to control its temperature during an accident.
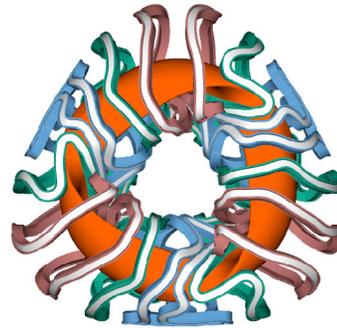

Fig. 3. Three field period ARIES-CS design option.

III. ACTIVITY AND DECAY HEAT

As a source term, the activity is used to generate the decay heat for the loss of coolant accident (LOCA) analysis and to evaluate the radiological hazards of the individual components. The results reported here pertain to the solids only. No attempt has been made yet to assess the activation level of the liquid LiPb breeder. The SiC structure generates the lowest activity and decay heat. Figures 4 and 5 compare the results of the SiC- and FS-based blankets evaluated for fully compacted, 100% dense materials, excluding all voids. The SiC initial values drop rapidly by 3-4 orders of magnitude at one day after shutdown while the FS values change slowly with time.

The WC-shield that replaces the blanket at specific locations generates the highest activity and decay heat. This high activation level is driven by the WC filler rather than the SiC or FS structures. The results for the remaining components (shield, VV, and magnet) are shown in Figs. 6 and 7 for the FS system. Similar behavior has been identified for the components of the SiC system. The magnet exhibits a very low activity, presenting no radiological hazard to the design.
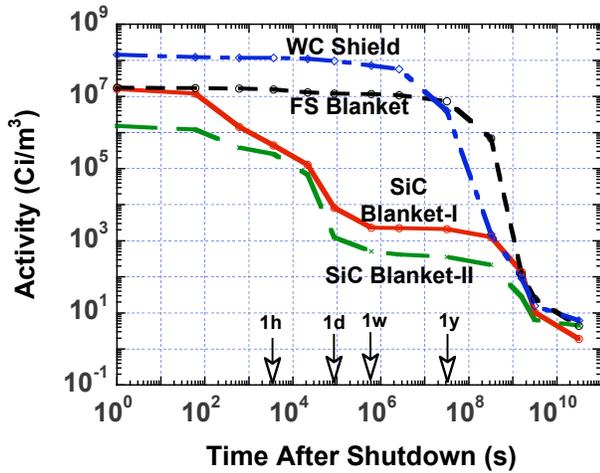
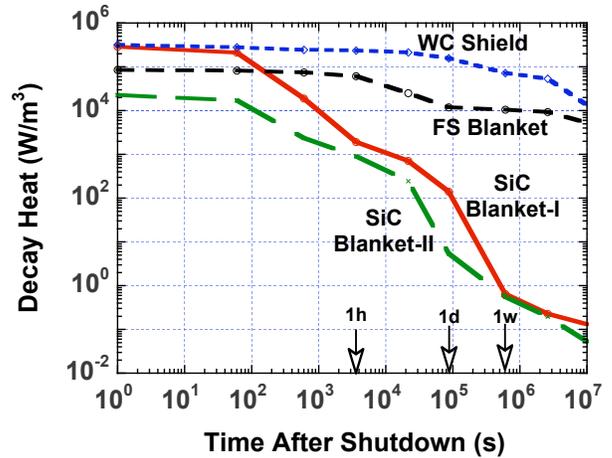Fig. 4. Specific activity of ARIES-CS blanket options.

Fig. 5. Decay heat of ARIES-CS blanket options.

IV. RADIOLOGICAL WASTE MANAGEMENT

Among the three radwaste management approaches envisioned for ARIES-CS, the disposal and clearance options have been investigated in detail for the solid structures while recycling is considered for specific materials, such as beryllium and solid/liquid breeders. This paper focuses on the disposal issue of solids. Reference 8 covers the details of the clearance approach and the highlights are reported here. For the interim ARIES-CS design, no serious effort has been devoted to the recycling approach.

There are two categories of materials that are candidates for disposal according to the official criteria:

high-level waste (HLW) and low-level waste (LLW). The US Nuclear Regulatory Commission (NRC) has defined two more categories for LLW: Class C and Class A. Class C waste requires engineered intruder barriers and a minimum disposal depth of 5 m. The lower level Class A waste must only meet the minimum packaging requirements. We evaluated the waste disposal rating (WDR) for a compacted waste using the most conservative waste disposal limits developed by Fetter[9] and NRC-10CFR61[10]. Here, we report the Class C WDR at 100 y after shutdown, allowing the short-lived radionuclides to decay. A WDR $\leq$ 1 means LLW and WDR > 1 means HLW. For a more elaborate discussion of the design criteria and limits, the reader is referred to References 7-9 and the references therein.
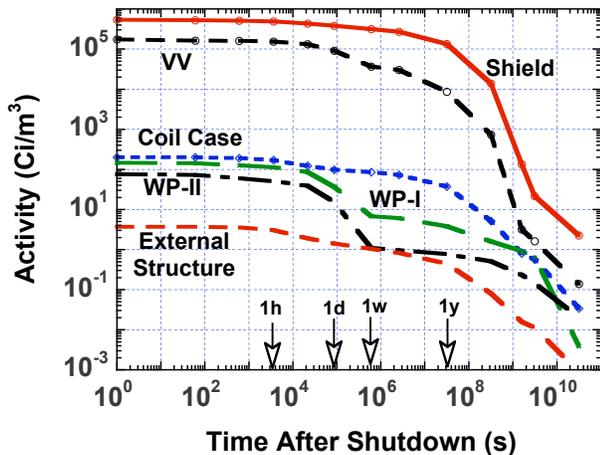

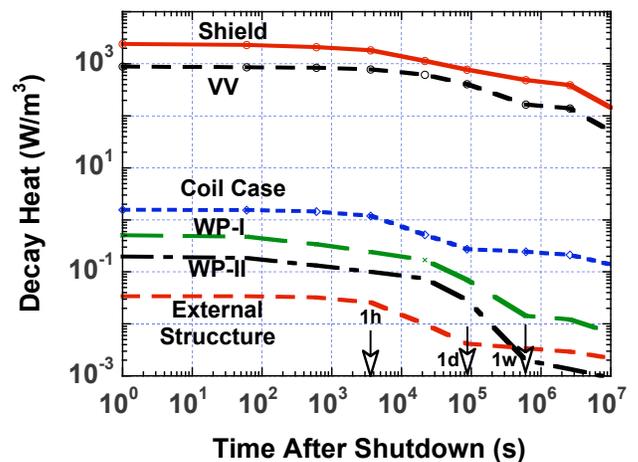Fig. 6. Activities of shield, VV, and magnet.

Fig. 7. Decay heat of shield, VV, and magnet.

WDR	SiC System	FS System
Replaceable components:		
FW/Blanket-I	0.03 (^{26}Al)	0.4$^{#}$ (^{94}Nb)
WC Shield	0.8 (^{108m}Ag, ^{99}Tc)	0.6$^{#}$ (^{108m}Ag, ^{99}Tc)
Permanent components:		
Blanket-II	0.06* (^{14}C)	---
Shield	0.5 (^{94}Nb)	0.7 (^{94}Nb)
Vacuum vessel	0.02 (^{94}Nb)	0.05 (^{94}Nb)
Coil case	0.02 (^{99}Tc)	0.02 (^{99}Tc)
WP-I	0.001 (^{99}Tc)	0.001 (^{99}Tc)
WP-II	0.12 (^{94}Nb)	0.1 (^{94}Nb)
External structure	0.001 (^{99}Tc)	0.001 (^{99}Tc)

* Based on NRC limits.
\# Averaged over FW, blanket, and back wall.

IV.A. Waste Disposal Rating

By definition, the WDR is the ratio of the specific activity (in Ci/m^3) to the allowable limit summed over all radioisotopes. Table II summarizes the WDR results and the main contributors to the waste. The WDRs are less than one, meaning all components qualify as Class C LLW at the end of the 100 y storage period after decommissioning. Note that the WDRs of the SiC-blanket, VV, and magnet are very low (< 0.1), to the extent that these components could even qualify as Class A LLW. Figure 8 displays the breakdown of the Class C and Class A wastes. Approximately, 63% of the SiC system waste is Class A. The remaining 37% would fall under the Class C low-level waste category. A reversed trend has been observed for the FS system (~34% Class A and ~66% Class C).

IV.B. Clearance Index

Clearance is the unconditional release of materials from radiologically controlled areas to the commercial market at the end of an interim storage period. After plant decommissioning, individual materials could be stored for a specific period (< 100 years), then released to the commercial market if the clearance index (CI) falls below one. The CI is the ratio of the activity (in Bq/g) to the allowable limit summed over all radioisotopes.

The clearance limits[11] developed by the International Atomic Energy Agency (IAEA) over the past two decades have been used worldwide for a diverse range of fusion concepts. With the emergence of the recent US standards for solid materials by the NRC, we took the initiative to compare the IAEA and US-NRC clearance limits. The work of Reference 8 represents the first time a comprehensive clearance assessment has been performed to identify the implications of the US clearance limits for fusion applications.

While the external components surrounding the magnets could potentially meet the clearance requirements, researchers have constantly applied the clearance criteria to the in-vessel components as well in an attempt to further minimize the volume of waste assigned for geological burial in repositories. Our results confirm that, based on the IAEA limits, none of the ARIES-CS internal components (blanket, shield, VV, and magnet) can be cleared from regulatory control or released to the commercial market at the end of the 100 y storage period.

The building surrounding the power core is subject to a less severe radiation environment and thus contains residual radioactivity. It appears feasible to release its constituents (concrete and reinforcing mild-steel) to the commercial market or nuclear industry after a relatively short storage period of 20 y or less, depending on the constituents (see Fig. 9). The reader is referred to Reference 8 for the implications of the US-NRC limits for the ARIES-CS design. Of interest is that the concrete dominates the low-level waste stream and its release shortly after plant decommissioning saves a substantial storage and disposal cost for such a large quantity, freeing ample space in the repositories for more radioactive wastes.
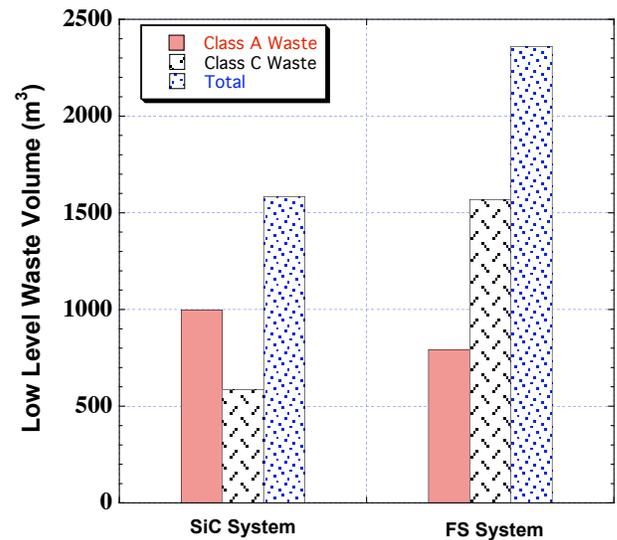

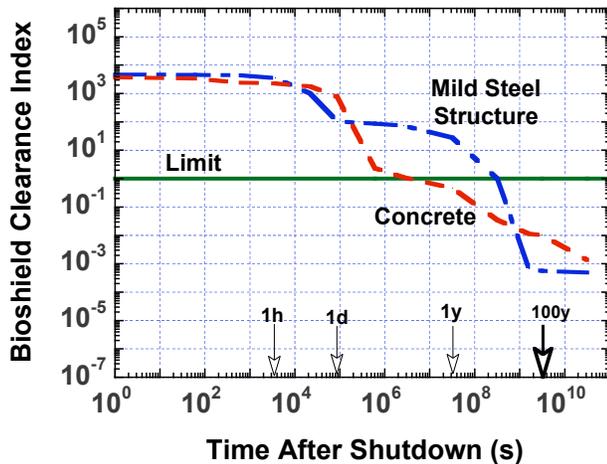Fig. 8. Breakdown of Class A and Class C LLW for ARIES-CS internal compacted components, including replacements.

Fig. 9. IAEA clearance index for ARIES-CS bioshield.

V. CONCLUSIONS

We performed a systematic activation assessment for the interim ARIES-CS design in the areas of activity, decay heat, and waste management to assure the system can meet the safety requirements. Two widely different systems based on SiC and FS structures were selected for this analysis and yielded favorable results. At intermediate times after shutdown (days-years), the SiC system offers 3-4 orders of magnitude less activity than the FS system and the decay heat for the SiC system drops sharply after shutdown, a salient feature for SiC. The WC local shield generates the highest activity and decay heat compared to the surrounding blanket regions.

Both SiC and FS systems have a low waste disposal rating that qualifies for a low-level waste classification. All components, including the WC-shield, qualify as LLW at the end of a 100 y storage period following the decommissioning of the plant. The SiC system offers a lower WDR. Class A LLW seems achievable for 63% of the SiC waste volume as opposed to 34% for the FS system. All the internal components (blanket, shield, VV, and magnets) must be disposed at LLW facilities after an interim storage period of 100 years. The external concrete building is essentially uncontaminated and suitable for clearance.

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