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ACTIVATION ANALYSIS FOR TWO MOLTEN SALT DUAL-COOLANT BLANKET CONCEPTS FOR THE US DEMO REACTOR

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The US has considered, among other options, two blanket concepts for Demo reactor in which helium is primarily used to cool the first wall (FW) and structure whereas molten salt (MS) is used as both coolant and breeder. Conventional reduced activation ferritic steel (RAFS, F82H) is used as the structural material in both blanket concepts. The low melting point Flibe (~380^{o}C) is used in the first option while the Flinabe (~305^{o}C) is used in the second option. In this paper, we present the results for assessing the radioactivity and decay heat. This assessment is performed separately for the structural material, the Be multiplier and the breeder (Flibe/Flinabe). The Class C waste disposal rating (WDR) was estimated for each material. For Flibe, Flinabe and Be the WDR is much lower than unity. However, the WDR for F82H is ~0.6-1.3. They are attributed to reactions with Mo and Nb present in F82H with levels of 70 wppm and 4 wppm, respectively. To ensure that F82H qualifies for shallow land burial, it is suggested to reduce these two impurities to ~50 and ~3 wppm, respectively.

I. INTRODUCTION

Several studies have considered molten salts as breeders as well as coolants in fusion reactors[1-4]. They exhibit attractive properties for fusion application such as low vapor pressure. In particular, these studies focus on Flibe (consisting of mole ratio of 2:1 of LiF and BeF_2) and Flinabe[5,6] (consisting of mole ratio of 1:1:1 of LiF, BeF_2 and NaF). Other attractive properties are: low chemical reactivity with air and water, low activation, adequate neutron moderation, and low electrical conductivity. The latter property lessens to a great extent concerns regarding pressure drops and forces due to the impact of magneto hydrodynamics (MHD) on the flowing of liquids in conduits and around and past penetrations and eliminates the need for using an insulating material between coolant and structural walls. These molten salts were considered for fission reactors but received less attention due to its poor neutron economy. In the past, they were also considered for fusion application but their poor tritium breeding capabilities draw away the attention of research to other breeders. Additionally, they have low thermal conductivity that leads to lower heat transfer capability. However, recent studies[7,8] have shown indeed that these molten salts could have adequate tritium breeding ratio (TBR) when a neutron multiplier, such as beryllium or lead, is used to enhance neutron population in the blanket. There are two types of Flibe that are under consideration, namely, high melting point (HMP) Flibe (459°C), and low melting point (LMP) Flibe (380°C). The mole ratio in the latter type is 1:1 of LiF and BeF_2 and its lower melting point improves plant thermal efficiency. However, LMP Flibe has much higher viscosity. The molten salt Flinabe, on the other hand, has the lowest melting point (~305°C) among these three molten salts but it requires more amount of multiplier[7,8].

Recent studies in the US are focusing on developing an attractive blanket concept for Demo reactors with molten salts as coolant and breeder[8,9]. Dual coolant (DC) concept is used in these studied where the first wall and structure are cooled with a separate helium circuit whereas the blanket itself is cooled with the flowing molten salt which acts also as a breeder. Because these blankets are planned to be tested in dedicated ports in ITER, which has a 10-year mission operation schedule, advanced structural material such as oxide dispersion-strengthened (ODS) steel[10] with maximum operation temperature of 800°C was excluded as the structural material since it requires long-term development. Rather, the conventional reduced activation ferritic steel (RAFS) alloy F82H (maximum operation temperature of 550°C) was considered. Two DC blanket options were selected and studied under Demo operation conditions. The first option utilizes LMP Flibe with 50% Li-6 enrichment and is denoted DC/LMP Flibe. Flinabe with 60% Li-6 enrichment was selected for the second option and is denoted DC/Flinabe. In both blankets options, a separate beryllium zone is added to enhance tritium production. The Demo reactor has a major radius of 5.8 m and an aspect ratio of 2.6 with a maximum neutron wall load, NWL, of 3 MW/m^2 at the outboard (OB) (~2 MW/m^2 at the IB) and an average NWL of ~2.5 MW/m^2 at the OB (~1.6 MW/m^2 at the IB). The blanket in both concepts has a thickness of 65 cm in the OB (40 cm in the IB), including a 5 cm-thick front Be zone (8 cm in the case of

Flinabe). The radial build in both blanket concepts was arrived at after several iterations to maximize the TBR while ensuring adequate radiation protection to the magnet, allowing rewelding of vacuum vessel, and making the shield a life-time component. The FW is estimated to last ~5 full power years before replacing the blanket. The results of this neutronics assessment are reported in a companion paper[8]. In this paper, we present the results for assessing the radioactivity and decay heat in these two blanket options for up to 1000 years after shutdown. This assessment is performed separately for the structural material, the Be multiplier and the breeder (Flibe/Flinabe). The average wall loading on the OB and IB is considered in the analysis and the modules are assumed to be ~8.3 m long in the poloidal direction.

II. THE DUAL COOLANT BLANKET CONCEPT

II.A. Description

Figure 1 shows a cut in the DC blanket in both blanket options. The FW and structure (including the stiffening ribs) are cooled with helium (shown in white arrows) which has a separate circuit with manifolds located at the back of the blanket. The LMP Flibe (or Flinabe in the second option) runs poloidally through perforated walls to cool the Be pebbles zone and then reaches the breeding zone where it acts as a breeder and coolant.

II.B. Radial Build

The radial build of the OB DC/LMP Flibe blanket is given in Table I. The two blankets with LMF Flibe and Flinabe have the same total thickness of 65 cm (40 cm in the IB). To arrive at an adequate local tritium breeding ratio (TBR), the beryllium zone in the DC/Flinabe blanket was increased to 8 cm (both in the OB and IB) at the expense of using a smaller breeding zone thickness. In this case, both blankets give a TBR of ~1.29 after several iterations of 1-D toroidal model calculations[8]. This value has a comfortable margin to account for uncertainties arising from approximations in modeling and nuclear data. The percentage of materials in each zone takes into account geometrical variation in the toroidal direction (e.g. ribs) shown in Fig. 1.

TABLE I. Radial Build of OB DC Blanket with LMP Flibe

Zone		Thickness (mm)	% Flibe	% FS	% Be	% He
1	FW front	3		100		
2	FW cooling channel	22		13		87
3	FW back	3		100		
4	Breeder front channel	20	93	3		4
5	Multiplier front wall	3	10	88		2
6	Be pebble bed	50	35	3	60	2
7	Multiplier back wall	3	10	88		2
8	Breeder back channel	20	93	3		4
9	Second wall	38		32		68
10	Breeding zone	288	93	3		4
11	Breeding/manifold	166	64	9		27
12	Back wall	34		66		34
	Total	650				

III. ACTIVATION ANALYSIS

The activation analysis was performed using the activation code DKR-PULSAR/A-2.0[11] along with the FENDL/A-2.0 data base[12]. In this analysis, the neutron flux is calculated using the 1-D transport code ANISN[13]. A shield zone (thickness of 30 cm OB, 40 cm IB) consisting of 70% F82H and 30% water was placed behind the IB and OB blankets followed by a 25 cm thick vacuum vessel which has the same material composition as the shield.

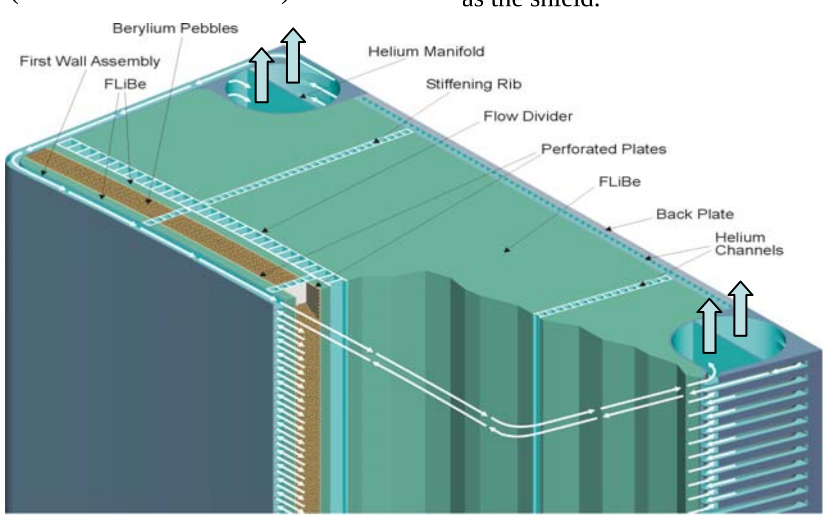

Fig. 1. Cut in DC-Be Blanket Showing He Flow Circuit.

The FW of the IB and OB at the mid-plane are placed at a radial distance of 3.47 m and 8.13 m from the center of the torous, respectively. The blanket lifetime used in the calculations is 5 full power years. The impurities in the F82H were accounted for in the calculations but no impurities were considered in the beryllium and breeders[18]. The breeder is circulating with different speeds in the coolant channels with the average speed dominated by the speed in the breeding zone where the coolant has the largest residence time. The Flibe (or Flinabe) coolant is assumed to spend ¼ the time in the blanket and ¾ of the time outside the reactor during the lifetime of the plant (30 full power years). It is estimated that the coolant spends ~144 sec in the reactor in each cycle where it is subjected to irradiation.

III.A. Radioactivity Inventory

The total activity generated in each material in the IB and OB modules of the DC/LMP Flibe blanket of a poloidal length of 8.3 m is shown in Fig. 2 as a function of time following shutdown.

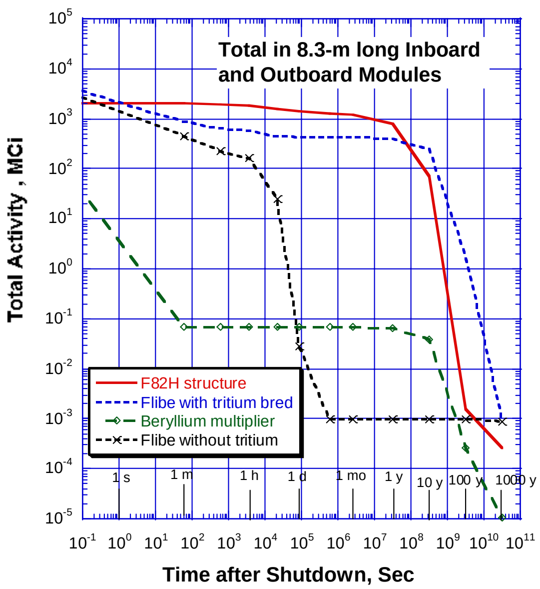

Fig. 2. Total Radioactivity in the DC/LMP Flibe Blanket.

After few seconds, the activity from the F82H structure dominates the activity inventory up to ~10 years when the activation from the Flibe starts to be the main contributor. The short and intermediate activity in F82H is dominated by Fe-55 ($T_{1/2}$=2.72 y) up to ~100 y, as shown in Fig. 3. The Flibe activity on the other hand is dominated by the bred tritium ($T_{1/2}$=12.33 y), and when removed, the short and intermediate activity is dominated by F-18 ($T_{1/2}$=1.83 h) generated from F-19(n,2n) reaction, O-19 ($T_{1/2}$=26.9 s) generated from F-19(n,p) reaction, and N-16 ($T_{1/2}$=7.13 s) generated from F-19(n,α) reaction, as shown in Fig. 4. These reaction types that lead to the destruction of fluorine have been reported in Ref. 14. As for the activity from beryllium, the main contributor is tritium isotope generated via Be-9(n,t)Li-7 reaction which dominates the total activation from few minutes up to ~100 y after shutdown. The total tritium produced in the Be over the life of the blanket is estimated to be ~2.9 kg.

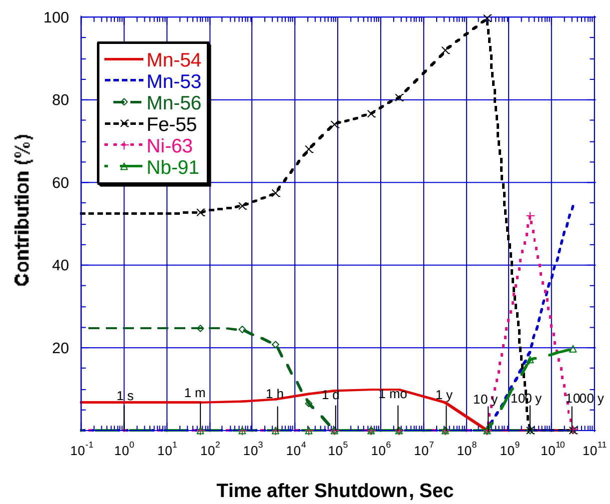

Fig. 3. Major Radionuclides Contributing to the Activity of the F82H Structure in the DC/LMP Flibe Blanket.

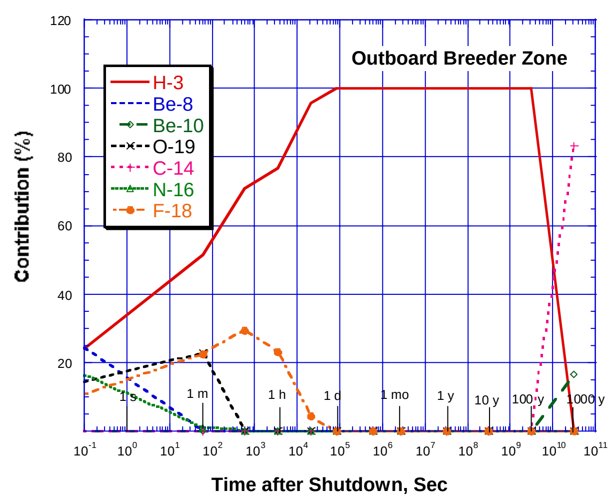

Fig. 4. Major Radionuclides Contributing to the Activity of Flibe in the DC/LMP Flibe Blanket.

A comparison of the total activity generated in the DC/LMP Flibe blanket and the DC/Flinabe blanket is shown in Fig. 5. The activity generated in the F82H structure is almost identical in both blankets. The inventory in beryllium is slightly larger in the DC/Flinabe case due to the larger Be zone in this blanket option (8 cm). The estimated tritium generated in Be is ~3.9 kg during the blanket lifetime. The activity generated in Flibe is also larger than in Flinabe by a factor of 1.5-2 in the time frame of few days to few years after shutdown. This is due to the lager breeder zone in the DC/LMP Flibe blanket. As in the Flibe case, and for the short and intermediate radioactivity inventory of Flinabe, H-3 and Be-8 are generated from Be and O-19, N-16, F-18, and F-20 ($T_{1/2}$=11 s) are generated from F-19 via the reactions mentioned earlier. However, due to the presence of sodium, the Na-24 ($T_{1/2}$=15 h) is generated from the reaction Na-23(n,γ).

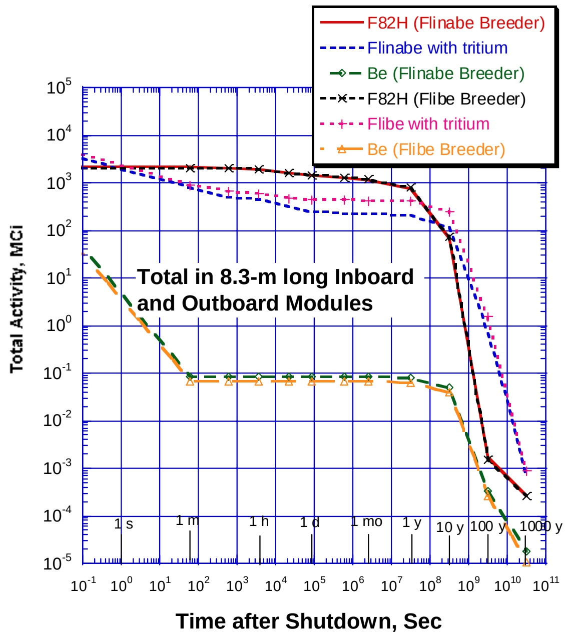

Fig. 5. Comparison between Total Activity in Each Material in the DC/LMP Flibe and DC/Flinabe Blankets.

III.B. Decay Heat

A comparison of the total decay heat generated in the DC/LMP Flibe blanket and the DC/Flinabe blanket is shown in Fig. 6. The decay heat in Be is the least among blanket constituents and is slightly larger in Flinabe case due to the larger Be zone. The decay heat in the structure is identical in the two blanket options, as shown in Fig.6. This feature is the same for the total activation generated in the F82H structure in both blankets.

In the DC/LMP Flibe blanket, the main contributors to the decay heat in the F82H structure are shown in Fig. 7. The Mn-56 ($T_{1/2}$=2.578 h) is the dominant contributor up to several hours after shutdown whereas the Mn-54 ($T_{1/2}$=312.12 d) dominates thereafter in the intermediate time after shutdown. Short-term (minutes) decay heat in Flibe is dominated by O-19 and N-16. The F-18 dominates the decay heat for few days after shutdown and H-3 takes the role of the main contributor thereafter, as shown in Fig. 8. On the other hand, there is an appreciable contribution to the total decay heat in Flinabe (the DC/Flinabe blanket) that is attributed to the generation of Na-24, up to few hours, and to the production of Na-22 ($T_{1/2}$=2.62 y), generated from the Na-23(n,2n) reaction, up to several years following shutdown. This explains the larger total decay heat (by 1-2 orders of magnitude) in this blanket option compared to Flibe (see Fig. 6), although the total activation from Flibe is larger (see Fig. 5).

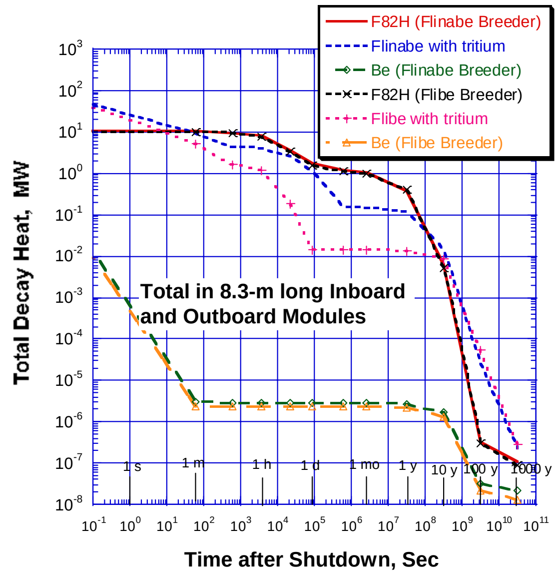

Fig. 6. Comparison between Total Decay Heat in Each Material in the DC/LMP Flibe and DC/Flinabe Blankets.

III.C. Waste Disposal Rating (WDR)

The WDR depends on the level of the long-term activation generated in both blanket options. For the F82H structure, Mn-53 ($T_{1/2}$=3.7 x 10^6 y) and Nb-91 ($T_{1/2}$=6.8 x 10^2 y) are the main contributors (see Fig.3). In Flibe (and Flinabe), the main contributors to the long-term activation are Be-10 ($T_{1/2}$=1.51 x 10^6 y) and C-14 ($T_{1/2}$=5730 y), as can be seen from Fig. 4.

The radwaste classification of the different components in the two blanket options was evaluated according to the Nuclear Regulatory Commission[15] (NRC) 10FR61 and Fetter[16] waste disposal concentration limits. The limits given are based on the assumption that all solid components are crushed before being disposed (no voids). Components having WDR >1, according to Class C limits, do not qualify for shallow land burial.

The WDR values for F82H structure in the DC/LMP Flibe blanket and the DC/Flinabe blanket are ~0.5 and ~0.6, respectively, based on the NRC limits, and is attributed to the generation of Nb-94 produced from the transmutation of niobium and molybdenum. The corresponding WDRs based on Fetter limits are 0.6-1.2, and 0.7-1.3, respectively, and are attributed mainly to the generation of Tc-99 and Nb-94. These radionuclides are generated from reactions with Mo and Nb present in F82H with levels of 70 wppm and 4 wppm, respectively. To ensure that F82H qualifies for shallow land burial, it is suggested to reduce these two impurities to ~50 wppm and ~3 wppm, respectively. The level of other impurities, such as Ag, is also suggested to be reduced in F82H to ~1 wppm according to other studies[17].

As for the Flibe in the DC/LMP Flibe blanket, the WDRs are 0.0002-0.002 (Fetter) and 0.01 (NRC). They are attributed to the generation of C-14 and Be-10. The corresponding values for Flinabe in the DC/Flinabe blanket are 0.0001-0.001 (Fetter) and 0.01 (NRC). Therefore, the breeder in the two blanket options is qualified for shallow land burial. This is also the case for beryllium for which the WDR is estimated to be ~0.0001 (Fetter) caused by the Be-10 generation.

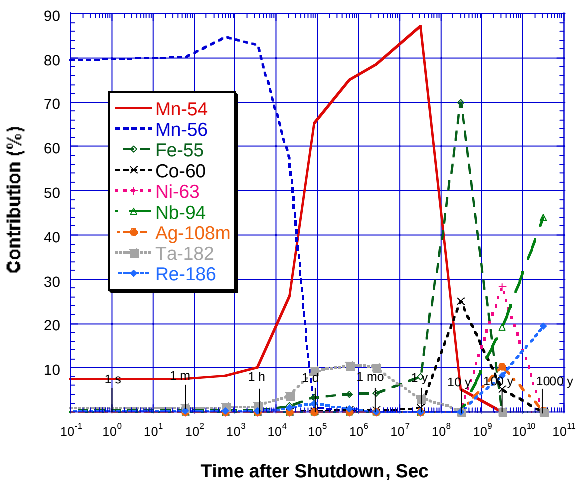

Fig. 7. Major Radionuclides Contributing to the Decay Heat of the F82H Structure in the DC/LMP Flibe Blanket.

IV. SUMMARY AND CONCLUSIONS

Two dual coolant (DC) blanket concepts were studied by the US for Demo reactor in which helium is used to cool the first wall (FW) and structure whereas molten salt is used as both coolant and breeder. The F82H conventional steel is used as the structural material. The low melting point "Flibe" (~380°C) is used in the DC/LMP Flibe option while the "Flinabe" (~305°C), is used in the DC/Flinabe option. The blanket in both concepts has a thickness of 65 cm in the OB (40 cm in IB), including a 5 cm-thick front Be zone (8 cm in case of Flinabe). The FW is estimated to last ~5 full power years before replacing the blanket. The radioactivity and decay heat, after shutdown, were assessed separately for the structural material, the Be multiplier and the breeder (Flibe/Flinabe). The total activity and decay heat in the F82H structure is very similar in both concepts. The Flibe activity in the DC/LMP Flibe blanket is larger than the Flinabe activity in the DC/Flinabe blanket by a factor of 1.5-2 during few days to few years after shutdown. However, the decay heat is much larger in the Flinabe by up to two orders of magnitude in the time frame of 1 hour-10 years after shutdown. The Class C waste disposal rating (WDR) was estimated for each material. For Flibe, Flinabe and Be the WDR is much lower than unity. However, the WDR for F82H is ~0.6-1.3 due to reactions with Mo and Nb present in F82H with levels of 70 wppm and 4 wppm, respectively. To ensure that F82H qualifies for shallow land burial, it is suggested to reduce these two impurities to ~50 wppm and ~3 wppm, respectively. The results of the present work is needed to assess safety concerns such as thermal response during accident conditions and the mobilization of the radiological inventories and site boundary dose following these accidents[18].

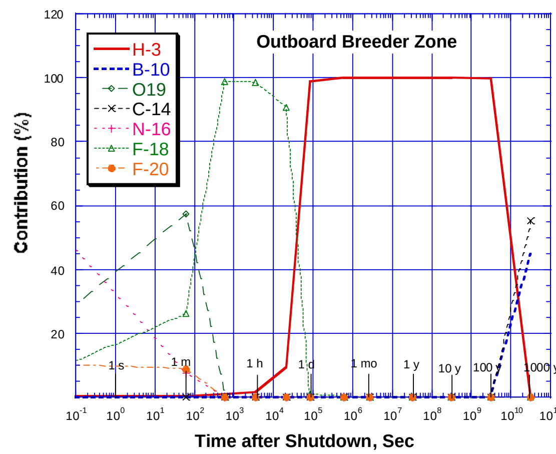

Fig. 8. Major Radionuclides Contributing to the Decay Heat of Flibe in the DC/LMP Flibe Blanket.

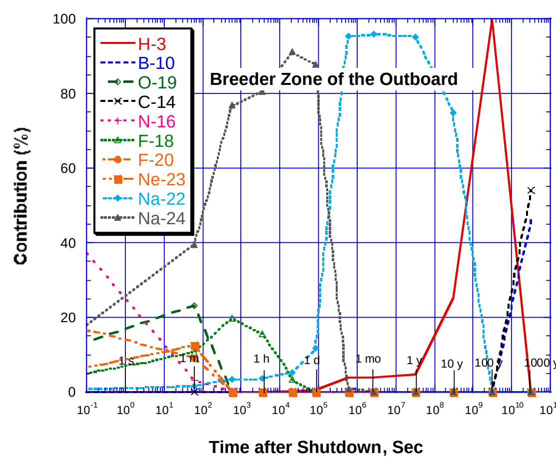

Fig. 9. Major Radionuclides Contributing to the Decay Heat of Flinabe in the DC/Flinabe Blanket.

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