Managing Fusion High Level Waste – A Strategy for Burning the Long-Lived Products in Fusion Devices

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FUSION TECHNOLOGY INSTITUTE

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L.A. El-Guebaly

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Abstract

Fusion devices appear to be a viable option for burning their own high-level waste (HLW). We propose a novel waste management strategy to eliminate (or minimize) the HLW generated by fusion systems. The main source of the fusion HLW includes the structural materials without impurity control, recycled materials, refractory metals, and liquid breeder cleanup and reprocessing systems. The basic idea involves recycling and reprocessing the waste, separating the long-lived radionuclides from the bulk low-level waste, and irradiating the limited amount of HLW in a specially designed module to transmute the long-lived products into short-lived radioisotopes or preferably, stable elements. The potential performance of the new concept seems promising. Our analysis indicated moderate to excellent transmutation rates could be achieved with neutron fluxes attainable in advanced fusion designs. Successive irradiation should burn the majority of the HLW or in practice reduce its volume considerably. The figures of merit for the concept relate to the HLW burnup fraction, neutron economy, and impact on tritium breeding. Hopefully, the added design requirements and complexity could be accommodated easily in fusion power plants and the cost of the proposed system would be much less than disposal in a deep geological HLW repository. Overall, this innovative approach offers benefits to fusion systems and helps earn public acceptance for fusion as a HLW-free source of clean nuclear energy.

1. Introduction

Safety and environmental issues are critical for public acceptance of fusion plants. In general, the public is likely to accept the nuclear industry if the waste is minimized and the high-level waste issue in particular is resolved. There seems to be a worldwide agreement among the fusion community on a variety of waste management options; most popular among these are the disposal, recycling, and clearing of the waste. For the disposal option, nuclear facilities generate two categories of materials according to the US radiological criteria: low-level waste (LLW) that qualifies for shallow land burial and HLW that qualifies for deep geological burial. Past ARIES studies showed that all in-vessel components cannot be cleared from regulatory control or released to the commercial market [1,2]. The question then is, "Should the LLW be buried near surface after being activated during once-through use or should it be recycled and reused in future nuclear facilities?" Note that recycling may generate HLW after several cycles [3-5]. Nevertheless, it is anticipated that recycling will be mandated for all fusion wastes to minimize the volume of waste assigned for geological burial.

To date, fusion waste management assessments have focused on the LLW, paying no attention to the HLW. There is no doubt the HLW aspect of fusion is of great concern because the potential hazards persist for thousands or millions of years before the waste decays to relatively safe levels. The question of whether the geological integrity of any waste repository can be assumed for a 1000-year period is controversial. There is also a secondary but important economic issue; the process of qualifying a repository for long-term disposal of HLW is very costly and could add several percent to the cost of electricity to support the HLW management activity. More importantly, it is ethically reprehensible to leave the HLW for future generations. For these reasons, means to transmute the fusion long-lived products into short-lived or stable nuclides are well worth exploring to alleviate the problems and reduce the hazards of the HLW.

We developed a clear and concise plan for the management of the HLW, primarily through a transmuting process to avoid sending the long-lived nuclides to HLW repositories [6]. The proposed concept requires advanced fusion power plants to burn their own HLW in a specially designed burning module, as discussed later. The process involves separation of the HLW elements from the waste stream followed by irradiation with fusion neutrons, attempting to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes. The products, therefore, could be committed to LLW disposal along with the majority of the fusion waste or released to the nuclear industry for reuse.

2. Waste classification

Since the inception of the ARIES project in the early 1990s, the LLW production has been considered a top-level requirement to demonstrate the environmental potential of fusion energy. This requirement represents an important advantage for fusion over fission. However, recent studies have indicated both MFE and IFE power plants will generate a finite quantity of HLW that requires deep geological burial. Typical fusion waste contains a few thousand tons of LLW [3] and a relatively small quantity (< one ton) of HLW byproducts. The breakdown of the waste is design dependent. Potential sources for the latter include long-lived radionuclides removed during the cleanup process of liquid breeders and recycling of fusion materials. Advanced high-temperature designs employing refractory metals (Mo, W, or Nb-based alloys) tend to generate sizable amounts of HLW. References 7 and 8 document the specific activity limits for both LLW and HLW based on the US waste classification standards. Numerous ARIES studies have identified fusion byproducts with high specific activities and long half-lives that contribute to the long-term fusion waste. These include:

- ^{94}Nb from steels, Nb- and V-based alloys, and superconducting magnet [3,9]
- ^{99}Tc from Mo-based alloys and steels [3]
- ^{186m}Re and ^{108m}Ag from W-based alloys [3,4]
- ^{63}Ni from steels and copper alloys [3,10]
- ^{26}Al from SiC/SiC composites [3]
- ^{208}Bi from LiPb breeder [3,5]
- ^{14}C from Flibe breeder [5].

3. HLW transmutation module

A burning module in a fusion device could be envisioned to be placed at the upper/lower extremity of the blanket or behind the divertor plates to minimize the impact on tritium breeding.

Four key elements are likely to determine the efficiency of the transmutation system: 1) the neutron flux level, 2) neutron spectrum, 3) neutron capture cross-section, and 4) duration of the irradiation cycle. HLW products with large capture cross section tend to burn out rapidly. A simple cylindrical model with 3 m radius has been developed to investigate the new concept and examine the elements that control the burnup process. Preliminary assessments indicated a remarkable increase in the burnup rate with flux and irradiation time. In an attempt to examine the

burning process using a realistic fusion environment, a 2 cm deep module was placed directly behind a 4 cm thick helium cooled first wall (30% steel and 70% He, by volume) and two options for the surrounding components were assessed: blanket or shield. The analysis showed superior neutron reflection and a higher burnup rate for the shielding option. This suggests a helium-cooled ferritic steel–based component to accelerate the burnup process. A 2 cm high by 2 cm deep, toroidally continuous module on the outboard of a tokamak could accommodate ~ 0.01 m^3 (~ 0.1 ton) of HLW. The impact of such a small module (covering < 1% of the first wall area) on the overall neutron balance and tritium breeding is negligible.

Although most ARIES power plants are designed to operate for 40 full power years at 85% availability, there are indications that advanced nuclear systems could extend the plant life beyond 50 y, or seek a license extension for 30 years or more, depending on performance. The neutron wall loading (Γ) is a metric for the neutron flux. Advanced tokamak designs offer a variety of Γ, ranging from 3 MW/m^2 at the upper/lower extremity of the outboard blanket [3] to 10 MW/m^2 at the outboard midplane [11]. Given the range of achievable Γ and operating time for advanced fusion devices, we evaluated the burning process for selected long-lived radionuclides using 3-10 MW/m^2, up to 100 y plant life, and time-dependent analysis to account for the change in the HLW inventory during irradiation.

4. Results

Throughout the study, the DANTSYS transport code [12] and ALARA activation code [13] with the most recent FENDL cross section library [14] have been used to optimize the transmutation system. Four long-lived nuclides were selected for this assessment: ^{94}Nb, ^{208}Bi, ^{99}Tc, and ^{63}Ni having half lives of $2x10^4$, $3.7x10^5$, $2.1x10^5$, and 100 years, respectively. The results for a moderate Γ of 3 MW/m^2 are presented in Figure 1. The notable difference in the burnup fraction reflects the wide variation in the capture cross sections of the radioisotopes. ^{99}Tc burns rapidly, losing 85% of the original atoms at 50 y and 97% at 100 y. We have selected ^{94}Nb to show the potential of two options that could enhance the performance. In Fig. 2, the effect of the neutron wall loading is given. As noted, the higher the Γ, the faster the burnup. With 10 MW/m^2, the irradiation period for 90% burnup is more than halved (50 y, instead of 120 y).

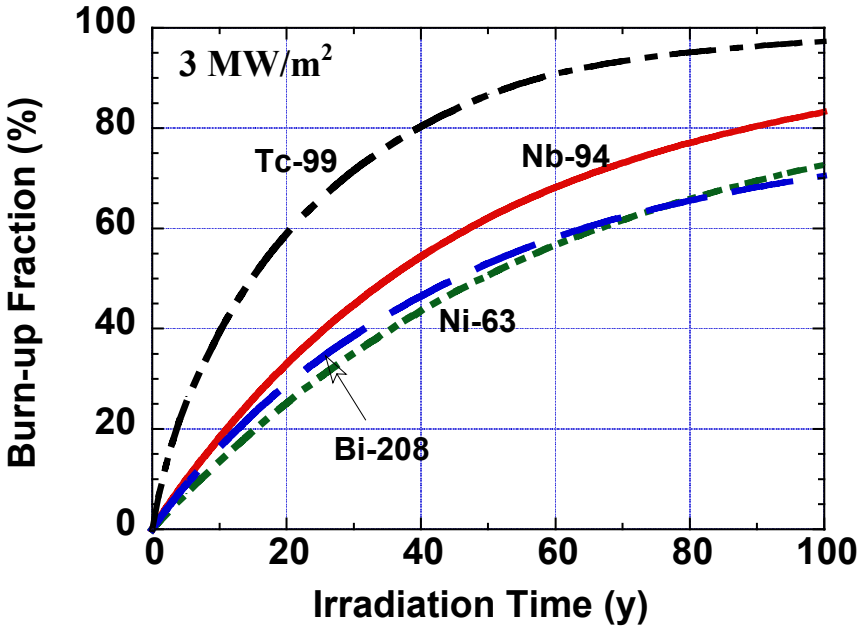

Figure 1. Variation of burnup fraction with irradiation time.

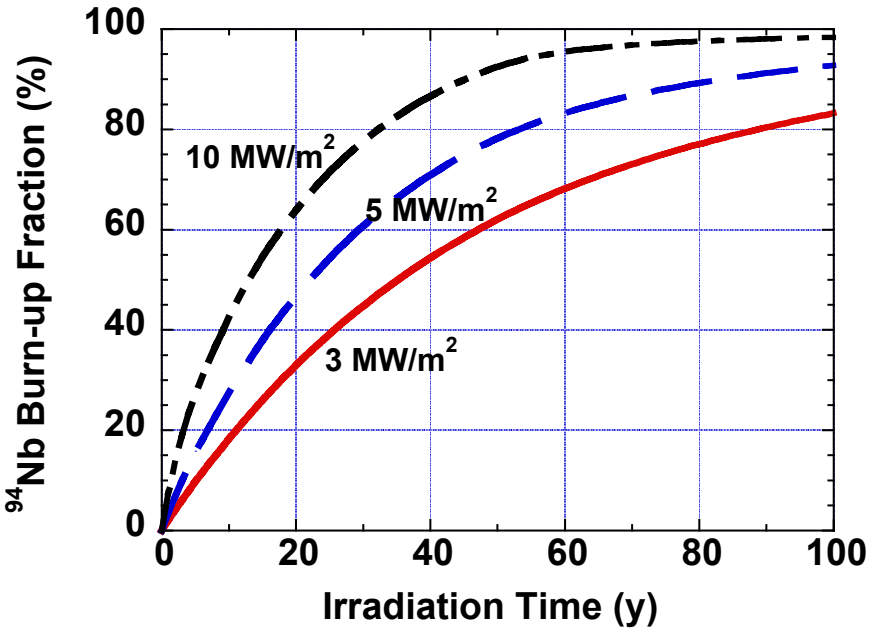

Figure 2. Increase of ^{94}Nb burnup fraction with neutron wall loading.

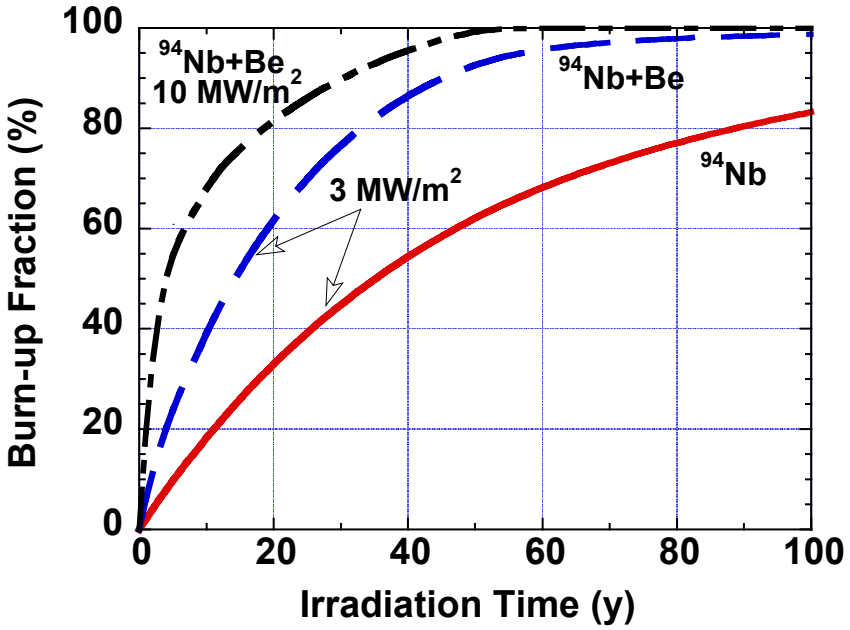

Figure 3. Sensitivity of ^{94}Nb burnup fraction to added Be for a range of neutron wall loadings.

A departure from the baseline design has been studied to illustrate the effect of changing the composition by mixing beryllium with waste. The presence of Be improves the neutron population through (n,2n) reactions and softens the spectrum slightly, resulting in a better capture activity for the waste. Figure 3 displays the remarkable improvement in performance due to Be. Even with a moderate Γ of 3 MW/m^2, 93% burnup can be achieved at 50 y while the higher Γ (10 MW/m^2) transmutes the majority (99%) of the waste during the same time period. These calculations assume a 50:50 mix ratio for Be:^{94}Nb, by volume. There could be a further improvement in performance if the mix ratio is optimized. Note that there is an additional benefit for the use of Be. It enhances the tritium breeding and helps compensate for the losses due to the burning module.

Clearly, irradiation of the HLW will not entirely destroy the long-lived radionuclides and may cause the generation of other long-lived radionuclides. Therefore, a subsequent separation process and re-irradiation of the unburned radionuclides and other long-lived byproducts would be required. Figure 4 shows the principal radionuclides contributing to the waste inventory after 50 y of ^{94}Nb burning using 10 MW/m^2. Inspection of the products reveals that ^{94}Nb transmuted into isotopes of Mo, Zr, and other elements (Kr, Rb, Sr, Y, Tc, Ru, Rh, Pd, and Ag), comprising 73 atom%, 3 atom%, and 10 atom% of the waste, respectively. The balance (14 atom%)

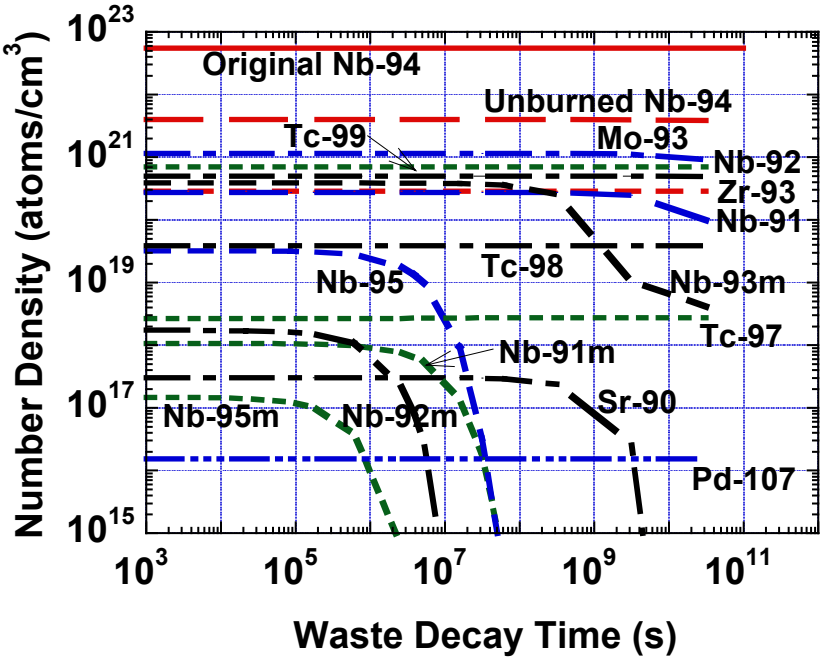

Figure 4. Radionuclide inventory of ^{94}Nb burned waste irradiated for 50 y with 10 MW/m^2 neutron wall loading. The top line represents the original ^{94}Nb inventory.

belongs to the unburned ^{94}Nb and other Nb isotopes. Of interest is that stable nuclides comprise 87 atom% of the waste while the remaining 13 atom% represents ~7 atom% unburned ^{94}Nb, ~6 atom% other long lived isotopes, and < 1 atom% short lived isotopes that decay rapidly within a few years (refer to Fig. 4). Based on the US standards [7,8], ^{91}Nb, ^{92}Nb, ^{93m}Nb, ^{93}Mo, ^{97}Tc, ^{98}Tc, and ^{99}Tc byproducts are likely to dominate the waste disposal rating (WDR) of the burned waste. Figure 5 shows the sensitivity of the WDR to the reprocessing and separation of the transmutation products. Removal of the unburned ^{94}Nb and all Nb isotopes could lower the WDR by 1-2 orders of magnitude. Further reprocessing and separation of $^{97-99}$Tc and ^{93}Mo open the possibility to drop the WDR far below unity, qualifying the remaining waste as Class C LLW or even Class A very low-level waste (WDR < 0.1), the least hazardous type based on the US federal classification [8].

It is recognized that, for individual fusion designs, the actual volume and physical and chemical characteristics of the waste should be evaluated. The reprocessing and separation of radionuclides and its byproducts should be considered by advanced fusion designs that adopt the recycling option to avoid the geological burial of the waste. During waste reprocessing, some long-lived transmutation products could be difficult to separate from neighboring

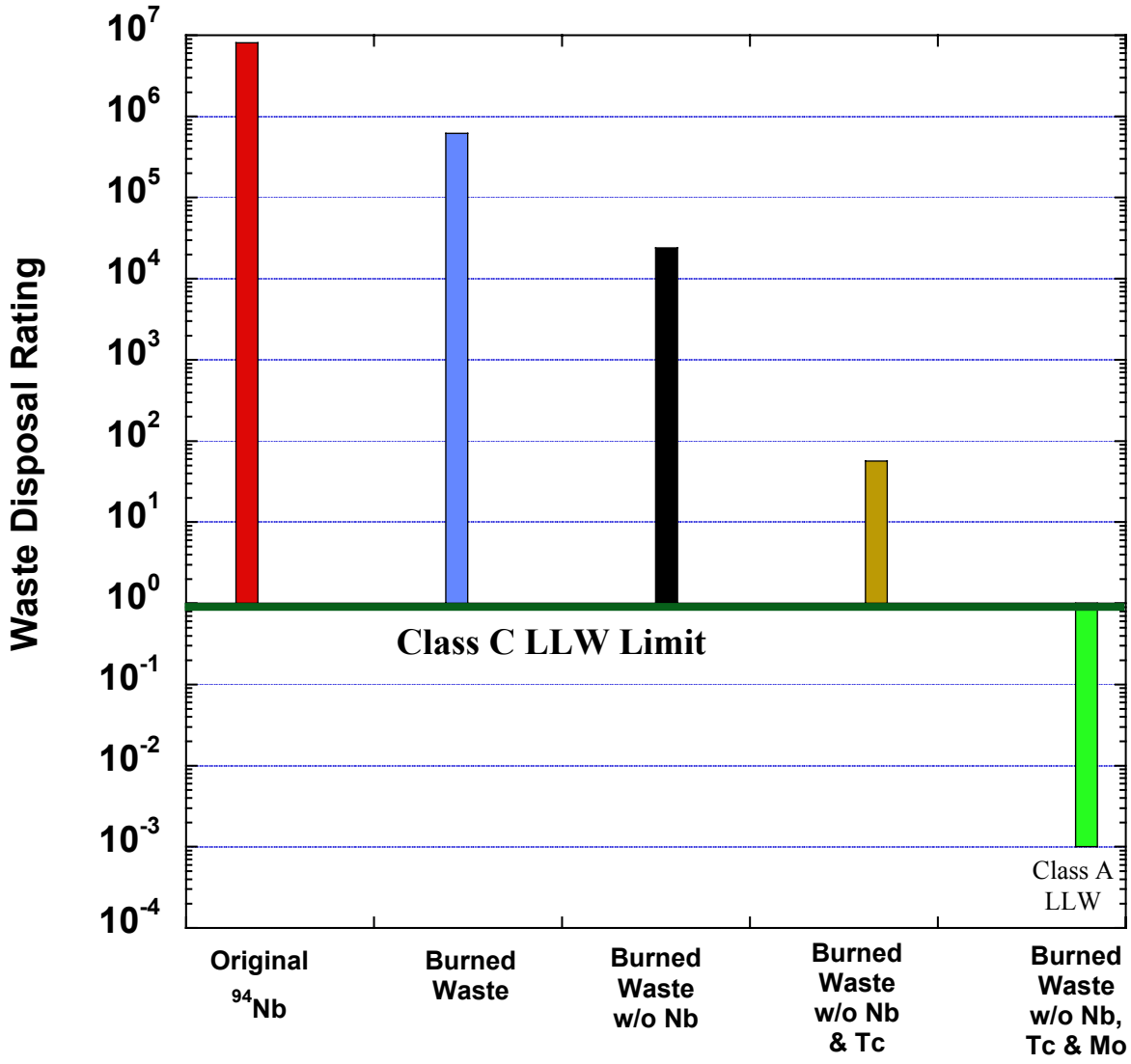

Figure 5. Reduction of WDR with removal of unburned ^{94}Nb and long-lived radionuclides.

elements using present-day technology. Since fusion may join the commercial market in 2050 or beyond, one could rely on advanced, extrapolated waste reprocessing technology to be developed during the next 50-100 years to provide 100% separation of the unburned and long-lived isotopes and therefore, assume the waste stream contains only stable nuclides or very low-level waste.

5. Concluding remarks

It appears that the deep geological burial of fusion HLW is preventable, but adds a few requirements that need further consideration. The proposed concept eliminates the need to transport and dispose the HLW in a deep geological repository. The main idea involves recycling and reprocessing the irradiated materials, separating the long-lived radionuclides from the bulk LLW, and requiring fusion machines to burn their own HLW. The general approach is to force the long-lived radionuclides to undergo successive neutron captures until they transmute into stable or short-lived elements. Several observations on the burning process are notable:

- HLW with large capture cross sections tends to burn out faster
- Burnup rate increases with neutron flux and irradiation time
- Beryllium improves burnup rate significantly
- Majority of HLW transmutes into stable elements.

Admittedly, the first irradiation process will not entirely transmute the long-lived radionuclides and therefore, a subsequent separation process and re-irradiation of the unburned radionuclides and other long-lived byproducts would be required. The final products, therefore, could be committed to LLW disposal along with the majority of the fusion waste, recycled within the nuclear industry, or hopefully, cleared from regulatory control and released to the commercial market. Extrapolations in waste reprocessing technology would have to be considered in concert with similar ground rules being adopted in advanced fusion designs.

This new approach may allow fusion designs to relax the LLW top-level requirement and permit the production of HLW, pending that recycling is a “must” requirement for all fusion wastes. Other compelling reasons for developing the concept include:

- Extending the service lifetime of LLW-limited components (such as the massive center-post of spherical tokamaks [10])
- Clearing many components from regulatory control by removing and burning the troublesome elements
- Employing high-temperature refractory metals to improve the design performance
- Relaxing stringent specifications imposed on impurity and alloying element concentrations (such as Nb, Ir, Ni, Ag, Cu, Co, Re, and Mo) that are based on LLW criteria [9], meaning no need to develop low-activation materials

– Employing off-the-shelf materials and shorten the pathway to fusion commercialization.

In summary, the success of this approach depends on the availability of reasonable space in fusion machines to burn their own HLW. The work recognizes fusion's potential role in providing HLW-free energy, but stresses that advanced waste reprocessing technology and isotope separation systems must be developed in 50-100 years – by the time fusion joins the energy market.

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