Need for Special Burning Module in Fusion Devices to Transmute Fusion High-Level Waste

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FUSION TECHNOLOGY INSTITUTE

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Abstract

Magnetic and inertial fusion power plants will generate high-level waste (HLW) that requires deep geological burial and poses risks to future generations. Potential sources for HLW include long-lived radionuclides removed during the cleanup process of liquid breeders, filtration of chamber buffer gases, and reprocessing of recycled materials. The ARIES waste management requirements developed for the U.S. power plants call for no or minimal HLW to increase public acceptance and decrease cost of HLW disposal. To date, fusion waste management assessments have focused on low-level wastes, paying no attention to the HLW. This report documents a novel concept that offers a potential solution for the fusion HLW to avoid the deep geological burial and help gain the public's acceptance for fusion energy. The concept requires advanced fusion power plants to burn their own HLW in a specially designed burning module. The process involves irradiating the HLW with fusion neutrons attempting to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes. An approach outlining the sequence of the transmutation process is proposed. It appears likely that the deep geological burial of fusion HLW is preventable, but adds a few design requirements.

1. Introduction

The issue of waste management has been studied simultaneously along with the development of the ARIES fusion concepts and designs. In the mid-1990s, the ARIES team established the top-level requirements for the U.S. fusion power plants with guidance from the U.S. power producers and utilities (1). The waste-specific requirement calls for no high-level waste production. This means commercial power plants should generate only low-level waste (LLW) that must either be disposed of near surface or recycled in a time frame which is within a human life span. In other words, the ARIES power plants should not deliberately produce HLW. The waste requirement was developed to gain public acceptance for fusion energy, offering no waste burden for future generations. The public is likely to accept the nuclear industry in general if the waste is minimized and the HLW issue in particular is resolved. Therefore, we recently focused new attention on the waste management options of ARIES and the ultimate means of disposing the HLW generated as a byproduct of the reprocessing and cleaning systems. This effort has led to the development of a new waste sub-requirement; that is, the HLW byproducts should be minimized.

This document suggests modifying the ARIES waste management approach and proposes a new strategy to minimize the HLW by burning the waste in the same fusion device without sacrificing the design performance. This new idea was promoted by observations the author recently made during the ARIES project meeting held in April 2002 at the University of Wisconsin-Madison. The new concept allows the majority of the fusion HLW to be removed and burned internally within the fusion device, eliminating the need to transport and dispose a large quantity of HLW in waste repositories. The basic idea is to irradiate the HLW in a specially designed module to transmute the long-lived fusion products into short-lived radioisotopes or preferably, stable elements by a series of nuclear reactions. Hopefully, the unburned HLW, if any, will be so small (several cups) that a small repository could hold the waste generated by many fusion power plants in a way that is acceptable to the public.

2. Potential Hazards of HLW

Typical fusion waste contains a few thousand tons of LLW (90% Class A waste and 10% Class C waste in ARIES-AT (2)) and a small quantity (liters-tons) of HLW byproducts. The latter creates challenges for storing for a very long time, perhaps a thousand or million years, before the waste decays to relatively safe levels. This means the potential hazards of the HLW persist for thousands of years to come. The main challenge is that the technology to retain HLW for a thousand years is not entirely satisfying. We can probably engineer containers to provide protection for LLW. For HLW, however, we must rely on the stability of the repositories. The question of whether the geological integrity of any waste repository can be assumed for a 1000-year period is controversial. Critics claim the water ingress has the potential of drawing long-lived isotopes into a future drinking water supply. 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.

3. Waste Management Options

There seems to be an agreement among the fusion community on a variety of waste management options; most popular among these are the disposing, recycling, and clearing of the waste. Because of the compactness of the ARIES devices, all in-vessel components and magnets cannot be released as cleared metals (3). 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 nuclear facilities? Recycling has the advantage of reducing the waste volume going to the disposal site, but has the drawbacks of costly remote handling, manufacturing, and processing systems. More importantly, recycling generates HLW after several cycles. The separation of the long-lived radionuclides from the waste stream helps concentrate the HLW in a small volume (4). Because of this HLW production, critics of recycling argue that the once-through use of large amounts of LLW is better than a smaller amount of HLW. The question that is raised at this point is the following: if permanent, deep geological disposal of the HLW is not acceptable to the public, what options remain? A novel waste-processing concept is proposed to minimize the volume of the fusion HLW, requiring each fusion power plant to burn its own HLW in a specially designed burning module.

It is pertinent to mention that the concept of burning the fusion HLW in fusion devices is new and concerns about nuclear proliferation issues are not relevant for fusion waste. In contrast, the reprocessing and burning of the fission HLW goes back to the early days of nuclear fission power. It was not until the late 1970'\s that the U.S. committed to bury the spent fuel intact in an attempt to slow the proliferation of nuclear weapons. Some argue, however, that leaving the fission waste and Pu underground presents counter-balancing proliferation concerns. At present, there is a strong support to process the spent fuel and recycle the waste in commercial fission reactors.

4. Characterization of Fusion HLW

Table 1 lists the long-lived radioisotopes produced in a typical fusion power plant. Short-lived fusion products with $T_{1/2} < 20$ y that lose most of their activity after being stored for 100 y are not included in this table. The 100 y cutoff represents the institutional control period at the disposal site where the LLW decays to an acceptable level. The waste is produced by single or successive neutron capture in solid or liquid materials. Several modes of decay are expected as results of neutron capture reactions: β emission, α particle decay, orbital electron capture, isomeric transition, and γ emission. The characteristic half-lives for major fusion products contributing to the long-term waste are shown in Table 1. The specific activity limits for Class C LLW are also included in Table 1. Instead of a single value, a range of limits has been assigned to some β emitters because of the uncertainties in Fetter's assumptions. Dividing the specific activity of each constituent by its limit and summing over all constituents, a waste disposal rating (WDR) of the waste mixture is determined. A WDR > 1 means the waste is high level and requires deep geological burial.

The U.S. Nuclear Regulatory Commission (NRC) waste classification is based largely on radionuclides that are important in fission facilities. In fusion power plants, the isotopes are different because of the different materials being considered and the different transmutation products that are generated. In the early 1990s, Fetter et al. (5) performed analyses to determine the Class C specific

Table 1. NRC and Fetter's limits for Class C disposal of radionuclides with half-life exceeding 20 y.

Radionuclides	Half-life (y)	NRC Limits (Ci/m^3)	Fetter's Limits (Ci/m^3)
Be-10	1.6e6		5,000
C-14	5.7e3	80	600 – 6,000
Al-26	7.2e5		0.09
Si-32	104		600 – 4,000
Cl-36	3.01e5		10 – 100
Ar-39	269		20,000
Ar-42	33		20,000
K-40	1.3e9		2
Ca-41	1.03e5		10,000 – 30,000
Ti-44	47		200
Fe-60	1e5		0.1
Ni-59	7.5e4	220	900
Ni-63	100	7,000	7e5 – 7e6
Se-79	6.5e4		50 – 500
Kr-81	2.1e5		30
Sr-90	28.5	7e4	8e5 – 7e6
Nb-91	680		200
Nb-92	3.6e7		0.2
Nb-94	2e4	0.2	0.2
Mo-93	3.5e3		4,000
Tc-97	2.6e6		0.4 – 4
Tc-98	4.2e6		0.01 – 0.08
Tc-99	2.13e5	30	0.06 – 0.6
Pd-107	6.5e6		900
Ag-108m	127		3
Sn-121m	55		7e5
Sn-126	1e5		0.1
I-129	1.57e7	0.8	2 – 10
Cs-135	3e6	8.4e3	---
Cs-137	30	4.6e4	5e4
La-137	6e4		200
Sm-151	90		5e7
Eu-150m	36		3e3
Gd-148	98		2e5 – 2e6
Gd-150	1.8e6		2e3
Tb-157	150*		5e3
Tb-158	150**		4
Dy-154	1e7		1000
Ho-166m	1.2e3		0.2
Hf-178m	31		9e3
Hf-182	9e6		0.2
Re-186m	2e5		20
Ir-192n	241		1
Pt-193	50#		2e8
Hg-194	520##		0.5
Pb-202	5.3e4		0.6
Pb-210	22.3		3e7 – 3e8
Bi-207	32.2		9e3
Bi-208	3.68e5		0.08
Bi-210m	3e6		1
Po-209	102		3e3
Ra-226	1.6e3		0.1 – 0.2
Ac-227	21.8		5e5 – 2e6

* 110 y quoted in literature
** 180 y quoted in literature
\# 60 y quoted in literature
\## 260 y and 444 y quoted in literature

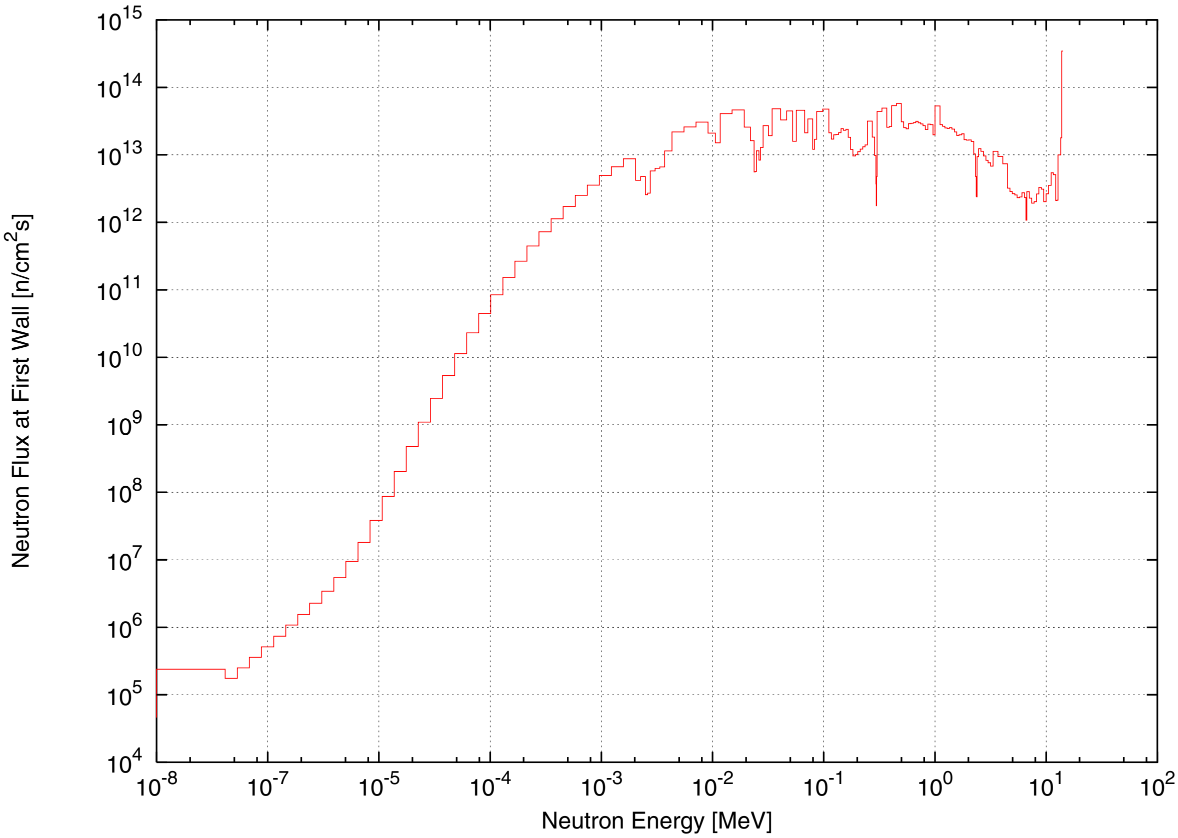

Figure 1. Typical first wall spectrum for advanced tokamak designs with 4 MW/m^2 neutron wall loading (2) [courtesy of P. Wilson (UW)].

activity limits for all long-lived radionuclides of interest to fusion using a methodology similar to that used in 10 CFR 61 (6). Although Fetter's calculations carry no regulatory acceptance, they are useful because they include fusion-specific isotopes, and therefore have been incorporated into the Department of Energy (DOE) Fusion Safety Standard (7). The ARIES approach requires all components to meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion waste. Hopefully, the uncertainties in Fetter's limits will be removed in the forthcoming NRC guidelines.

5. Transmutation Module Design Considerations

A burning module in a fusion device could be envisioned to be located at the upper/lower extremity of the blanket to minimize the impact on tritium breeding. It is not clear yet if the 14 MeV neutrons are absolutely required for the transmutation of fusion HLW. Therefore, it is possible to irradiate the waste using the hard spectrum right behind the first wall or the soft spectrum at the back of the shield. Figure 1 shows a typical fusion spectrum at the first wall peaking at 14.1 MeV. This peak contains ~15% of the total neutron flux and diminishes as one moves radially away from the first wall.

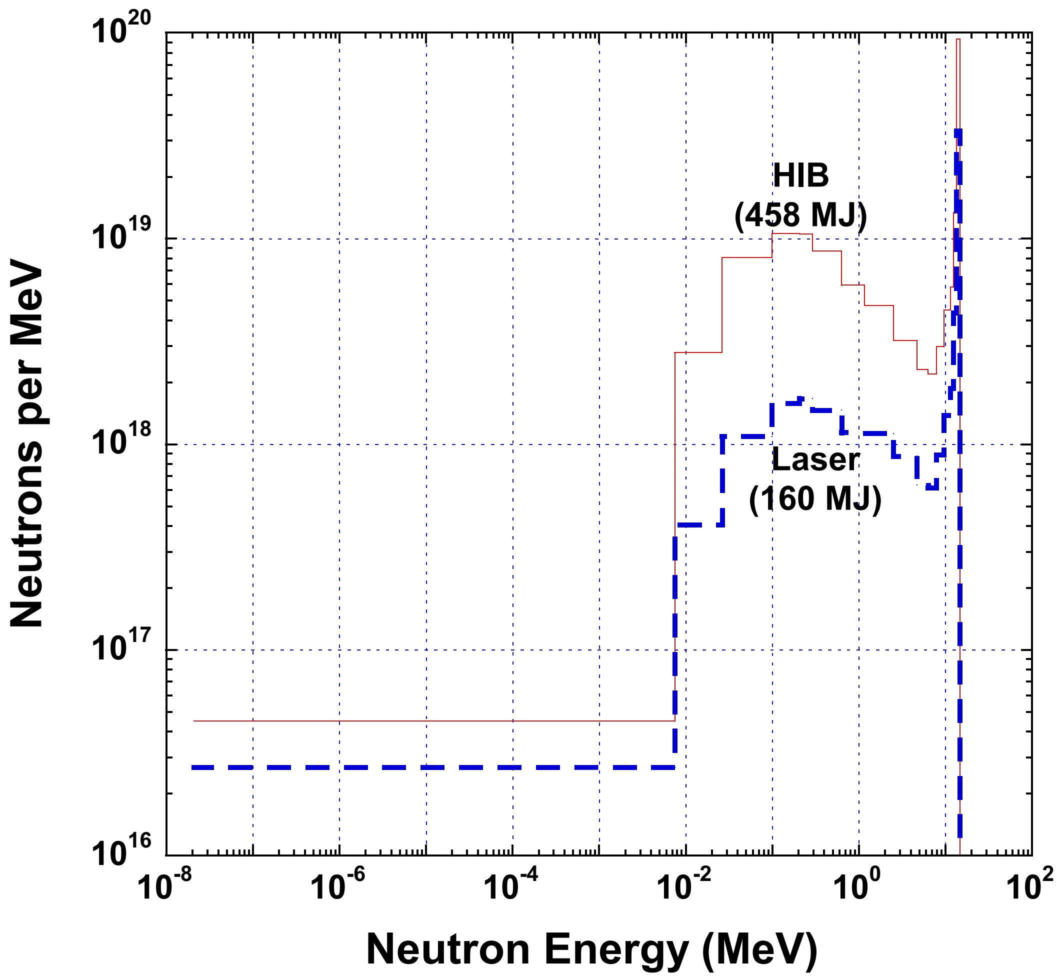

Figure 2. Neutron spectra for ARIES-IFE laser and HIB targets [courtesy of J. Perkins (LLNL)].

The basic design of the transmutation module is likely to be identical for both magnetic fusion energy (MFE) and inertial fusion energy (IFE) even though the confinement mechanisms and neutron source spectrum are quite dissimilar. The 14.1 MeV neutrons initially constitute ~ 80% of the MFE and IFE fusion energies. During burn, the IFE neutrons experience many collisions with the dense target materials. As a result, the neutrons moderate and lose a fraction of their original 14.1 MeV energy to the target materials making it possible for some neutrons to moderate to energies below 10 keV in less than 50 picoseconds. The computed neutron energy spectrum from the laser and heavy ion beam (HIB) targets are shown in Figure 2, having average neutron energies of 12.4 MeV and 11.8 MeV, respectively. The results relate to the 160 MJ laser target yield and 458 MJ HIB target yield of the ARIES-IFE designs (8).

6. HLW Transmutation Process

The general approach in the HLW transmutation scheme is to force the long-lived nuclides to undergo successive neutron captures until they transmute into stable or short-lived nuclides. The products, therefore, may be committed to LLW disposal along with the majority of the fusion plant waste.

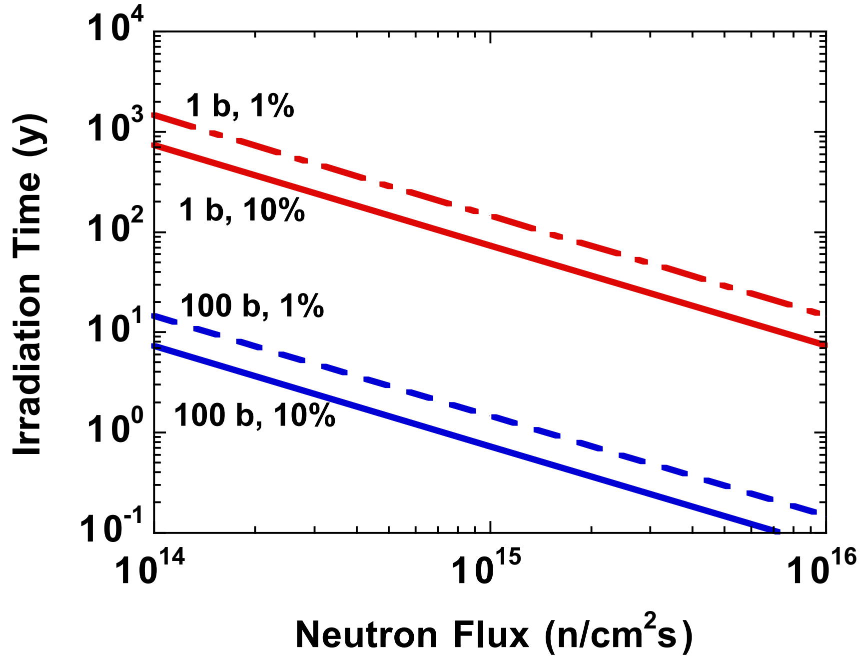

Figure 3. Variation of irradiation time with the neutron flux required to burn 90-99% of the inventory of radionuclides with 1-100 barn capture cross sections.

Admittedly, irradiation of the HLW will not entirely destroy the long-lived radionuclides. This would require a separation process and re-irradiation of the nuclides, which are not burned during the first cycle. Successive irradiation would hopefully burn all the HLW or in practice, reduce its volume considerably. Ideally, the processing step would require 100% separation of the short-lived and unburned long-lived isotopes. We could rely on advanced, extrapolated waste reprocessing technology; therefore, assume that the disposed waste stream contains only nuclides with short half-lives.

Four key elements are likely to determine the efficiency of the transmutation system: the neutron flux level, neutron spectrum, neutron capture cross section, and duration of the irradiation cycle. HLW products with a large capture cross section will burn out rapidly. The capture cross section could be large in the thermal regions. Therefore, it is possible that a large reduction in the HLW inventory could be achieved with the thermal flux rather than with the fast flux. To develop a goal for the flux level required at the transmutation module, consider the equation that describes the change of nuclide density with time due to both transmutation and natural decay at a specific location:

$$N(t) = N_o \, e^{-\sigma_c \Phi t - \lambda t} \quad ,$$

where λ is the decay constant and N_o is the initial nuclide density at t = 0, Φ is the energy integrated flux, and σ_c is the energy averaged capture cross section weighted by the neutron spectrum. Because the HLW radionulides have long half-lives, they tend to burn out at a faster rate compared to their rate of decay. For long-lived nuclides, λ is small and the natural decay component of the equation could be ignored. Therefore, the above equation can be simplified to

$$N(t) / N_o = e^{-\sigma_c \Phi t} \quad .$$

Suppose the goal is to reduce the HLW inventory to a small fraction of its initial value (e.g., 1 or 10%). Solving for the irradiation time, t, we have

$$t = \frac{\ln \frac{N(t)}{No}}{\sigma_c \Phi} \quad .$$

Given a range of achievable fluxes in fusion devices, one can estimate the time needed to achieve certain reduction in the waste inventory. Note that the time is inversely proportional to the capture cross section and flux, meaning the higher the cross section and flux, the shorter the irradiation time.

Figure 3 displays the time required to achieve 1-10% of the initial inventory as a function of the neutron flux for radionuclides with capture cross sections ranging from one to 100 barns. The dotted area defines the design window for the transmutation module. Fluxes ranging from 10^{15} to $5x10^{15}$ n/cm^{2}s are attainable at the upper/lower ends of blanket in fusion devices with 2-4 MW/m^2 neutron wall loading at the module surface. Examining Fig. 3, several observations can be made:

- Excellent burnup is achieved for radionuclides with $\sigma_c \geq 100$ barns even at flux levels below 10^{15} n/cm^{2}s,
- Relaxing the requirement on the unburned fraction from 1% to 10% shortens the irradiation time by a factor of two,
- To keep the irradiation time comparable to the plant lifetime (~40 y), radionuclides with higher σ_c than 100 barns require a flux level on the order of $10^{13} - 10^{14}$ n/cm^{2}s. Such fluxes could be achieved at the back of the module and/or in low-performance fusion devices with lower neutron wall loadings,
- If σ_c << one barn, a 10% burnup may be impossible to achieve during the 40 y plant life. This would mandate reprocessing and re-irradiation in other fusion facilities. Alternatively, a higher unburned fraction than 10% could be allowed for radionuclides with σ_c << one barn.

7. Neutronics of Transmutation Module

The goal of the neutronics study includes identifying the dimension and location of the module that has a minimal impact on tritium breeding, the neutron wall loading at the module surface, and the initial neutron flux and spectrum within the module. Once these items are identified, the transmutation performance of the module will be evaluated using time-dependent analysis to account for the change in the isotopic composition during irradiation. The system investigated could either employ stagnant solid HLW or HLW dissolved in a flowing liquid. The fusion power core design will be adopted from the ARIES-AT (2) and/or ARIES-IFE (8) designs. The nuclear analysis will determine the optimum operating parameters for the individual long-lived radionuclides and the achievable burnup fraction as a function of the irradiation time. The DANTSYS transport code (9) and the ALARA activation code (10) with the most recent FENDL cross section library will be used to optimize the system.

8. Concluding Remarks

We propose a new strategy to minimize the fusion high-level waste. Fusion devices appear to be a viable option well worth exploring for burning their own HLW generated as byproducts of the cleanup and recycling processes. Our study of the waste management alternatives has indicated that separation of the HLW followed by a transmutation process in a specially designed burning module seems to be an effective strategy to avoid the deep geological burial of the HLW. Preliminary analysis indicated moderate to excellent transmutation rates could be achieved with flux levels on the order of $5x10^{13}$ n/cm^{2}s – $5x10^{15}$ n/cm^{2}s that are attainable in advanced fusion designs. The success of this new concept will depend on the availability of a reasonable space in fusion machines to burn the HLW. To demonstrate the viability of the concept, the impact of the transmutation module on the fusion device and the waste management scheme should be evaluated. The figures of merit for the concept relate to the burnup fraction, neutron economy, and impact on tritium breeding and power balance. The concept is at an early stage of development and no attempt has been made to optimize the system. However, its potential performance seems promising. Future work will identify the optimum design parameters for the long-lived radionuclides and the evolutionary behavior of the HLW in the transmutation module. Hopefully, the added design requirements and complexity could be accommodated easily and the cost of the proposed system will be much less than disposal in HLW repositories.

Acknowledgements

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