UCRL-JC-134830
PREPRINT

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This paper was prepared for submittal to the
First International Conference on Inertial Fusion Sciences and Applications
Bordeaux, France
September 12 - 17, 1999

August 1999

Safety and Environmental Advantages of Using Tritium-Lean Targets for Inertial Fusion Energy

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Abstract

While traditional inertial fusion energy target designs typically use equimolar portions of deuterium and tritium and have areal densities (ρr) of ~ 3 g/cm^2, significant safety and environmental (S&E) advantages may be obtained through the use of high-density (ρr ~ 10 g/cm^2) targets with tritium components as low as 0.5%. Such targets would absorb much of the neutron energy within the target and could be self-sufficient from a tritium breeding point of view. Tritium self-sufficiency within the target would free target chamber designers from the need to use lithium-bearing blanket materials, while low inventories within each target would translate into low inventories in target fabrication facilities. Absorption of much of the neutron energy within the target, the extremely low tritium inventories, and the greatly moderated neutron spectrum, make "tritium-lean" targets appear quite attractive from an S&E perspective.

1. Introduction

One requirement of traditional inertial fusion energy (IFE) power plant designs is the need to breed large quantities of tritium to replace that which is burned (~ 0.4 kg/day for a 1 GW_e plant). This necessitates the use of lithium-bearing blanket materials, which poses a considerable limitation in the choice of breeder and structural materials. Targets typically operate with areal densities (ρr) of about 3 g/cm^2, and thus, much of the neutron energy escapes from the target and is available for damage and activation of first wall and blanket materials. Previous work has explored alternate fuel cycles such as D-D and D-^{3}He, but these concepts have proven undesirable due to the need for ρr ~ 10 g/cm^2 and the excessive driver energies that are needed to reach such regimes.[1-2] Recent work, however, has focused on the possibility of using a fast igniter concept to make such designs feasible at driver energies of 7-10 MJ.[3-4] Ongoing work by D. Callahan (submitted for publication) increases the coupling efficiency to 28% – further reducing driver energies to 4-5 MJ.

With such high values of ρr, these targets could use a fuel composition significantly different from traditional target designs with equimolar portions of D and T. With the ability to use tritium percentages as low as 0.5%, these targets are dubbed *tritium-lean*.[3] The large ρr of such targets allows many secondary fusion reaction to occur and such targets may be self-sufficient from a tritium breeding point of view and the power plant would be able to operate without a lithium-bearing breeding material. A wider range of blanket materials becomes viable, and thus, they may be selected based upon superior safety and environmental (S&E) performance rather than tritium breeding ratio (TBR).

Here, we compare the S&E characteristics for a tritium-lean target to those for a traditional D-T target with $\rho r = 3$ g/cm^2.

2. Calculational assumptions

The present work compares a power plant utilizing tritium-lean targets to the HYLIFE-II power plant, which features a thick-liquid Flibe protection scheme and stainless steel 304 (SS304) first wall.[5] S&E indices are calculated using similar assumptions and identical cross section and decay libraries.

2.1 HYLIFE-II model

The use of a thick-liquid protection scheme in the HYLIFE-II design is motivated by the desire to reduce radiation damage such that the first wall is a lifetime component. Assuming a plant lifetime of 30 full-power years (fpy), a first wall radius of 3.0 meters, and a 100 dpa limit, a Flibe pocket 56-cm-thick is required.

For a power plant size of 1000 MW_e, HYLIFE-II has a thermal power of 2675 MW.[5] This is generated with a fusion power of 2257 MW, a blanket energy multiplication factor of 1.136, a driver deposition of 30 MW, and a coolant afterheat of 80 MW. The 1-D TBR is 1.21. The repetition rate is 6 Hz.

2.2 Tritium-lean model

A target design featuring only 0.5% tritium has been selected for the present work. Since a fast igniter is used, the tritium would be present in the D-T seed (hotspot) only. *Table I* summarizes the key features of the tritium-lean target design that is assumed here. The reader should see reference 3 for further information on this target design. The tritium-lean target requires an internal energy of 1.15 MJ.[3] For a coupling efficiency of 28%, a driver energy of only 4.1 MJ would be needed. Although the initial target is comprised of only 0.5% tritium, a large portion of the energy is generated by D-T fusions.

Table I. Key features of the tritium-lean target.[3]

Parameter	Value
Fuel mass (T mass)	19.6 mg (156 μg)
Average fuel density	1000 g/cc
Target ρr	16.8 g/cm^2
Reaction breakdown: (% total fusions/% energy release)	D-D = 60.5/23.9 D-T = 28.8/54.7 D-^{3}He = 10.7/21.4
Target yield	1330 MJ

The D-T seed contains 20% tritium, and the burn wave propagates from the hotspot into the main fuel. The bulk of the D-T and D-^{3}He reactions would occur in the main fuel from the T and ^{3}He products of the two branches of the D-D reaction. Due to the high density of the tritium-lean target, much scattering occurs and the spectrum is rather soft relative to a traditional D-T target. *Figure 1* shows the neutron spectra emerging from a traditional and tritium-lean target. The traditional target has been normalized to the tritium-lean yield for easier comparison. Note that the traditional target has a significantly harder spectrum and that the tritium-lean target has many more low-energy neutrons.

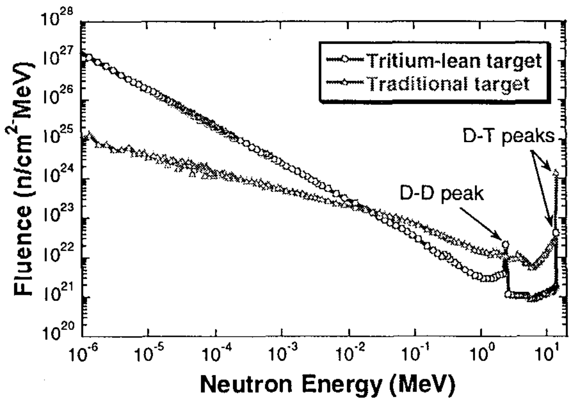

Fig. 1. Significant neutron scattering occurs within the tritium-lean target.

The tritium-lean power plant that is analyzed here adopts a basic design principle from HYLIFE-II–the liquid pocket is sized to obtain a first wall lifetime of 30 fpy. Since the internal breeding of the tritium-lean design eliminates the need for lithium-bearing materials, a boric oxide (B_2O_3) glass has been selected as an example due to its low activation. B_2O_3 is a noncombustible powder or crystal when solid. It has a melting point of 450 °C and a boiling point of 1500 °C. A detailed design considering vapor pressure, power conversion, tritium-retention, etc. has not been completed.

A B_2O_3 pocket thickness of 40 cm results in a damage rate of 3.1 dpa/fpy, and thus, a first wall lifetime of 32 fpy. The thinner blanket results from scattering within the target and the shorter neutron mean free path in B_2O_3. Other than the coolant and pocket thickness, the HYLIFE-II and tritium-lean models are consistent.

Working back from the desired thermal power of 2675 MW and using the calculated multiplication factor of 1.376, a required fusion power of about 1940 MW is obtained. Given the target yield of 1330 MJ, the repetition rate is 1.5 Hz. The driver power of 7 MW and B_2O_3 coolant afterheat of 5 MW are insignificant in the overall power balance.

Each tritium-lean target initially would contain ~ 156 μg of tritium. Since the majority of fusion reactions are not D-T, the usual way of defining the TBR has little meaning. Instead, one can consider a tritium balance. With 156 μg of tritium, each target includes 3.1×10^{19} tritons. Tritons are created in the target in three ways: as a reaction product from a branch of the D-D reaction, from $^{3}He(n,p)T$ reactions, and via $D(n,\gamma)T$ reactions. Tritons are destroyed in D-T fusions and via T(n,2n)D reactions. Considering the initial inventory and the destruction and creation mechanisms, 1.39 tritons emerge from the target for every one that is injected into the chamber. An additional 0.10 tritons are created in the B_2O_3 liquid via (n,T) reactions on the two boron isotopes. With the target and blanket tritium production, a facility using tritium-lean targets and a B_2O_3 blanket could produce an excess tritium inventory of about 10 g/d. This actually may be undesirable from an S&E perspective, but the target design could be tweaked to reduce the production of excess tritium.

3. Results

To enable comparison between the tritium-lean and HYLIFE-II designs, a number of radiological indices have been calculated. For accident hazards, the total radioactivity has been calculated. Activity, while simple to calculate, is not terribly useful due to the large difference in the hazard posed by various radionuclides. Nonetheless, it does provide some sense of how well one must contain the radioactive inventories in order to maintain accident doses below a certain level. True accident doses cannot be calculated accurately without use of detailed models that consider credible accident scenarios and the use of experimental data on radionuclide release fractions. The present work is conceptual in nature, and thus, this type of detailed analysis is not attempted here.

Waste management is a key area of S&E. A comprehensive waste management assessment must consider more than just the waste disposal rating (WDR). WDR does not account for the volume of waste, and thus, can bias design, material, and maintenance choices towards generation of larger quantities of low-level radioactive waste. In the present work, WDR is acceptable for comparison, because the waste volumes are nearly identical in the two cases.

3.1 Accident hazards

The total radioactivity in the first wall, coolant, and blanket is plotted in *figure 2* as a function of cooling time following 30 fpy of operation. At all cooling times, the HYLIFE-II activity exceeds that of the tritium-lean concept. At early times (minutes to hours), the HYLIFE-II activity is greater by ~ 200× due to the creation of large quantities of ^{18}F in the Flibe pocket. At cooling times of ~ 12 hours to 100 years, the tritium-lean inventory is lower by a factor of 5-10.

The radioactivity in the tritium-lean case is dominated by the activation of the SS304 first wall. If the B_2O_3 pocket were thickened to achieve the same mass as in the Flibe for HYLIFE-II, the SS304 activity would drop by another factor of 3-5.

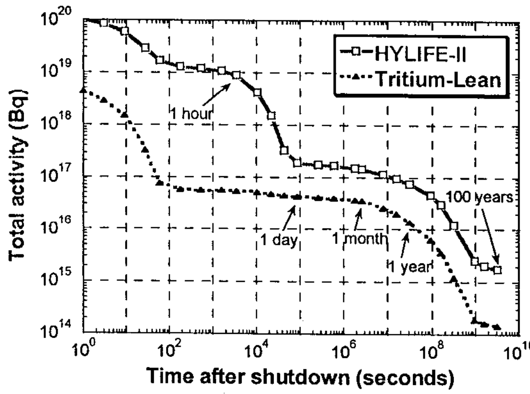

Fig. 2. The total radioactivity in a power plant utilizing tritium-lean targets would be considerably less than that in one using traditional targets.

Not shown in the figure is the radioactivity associated with the tritium that would be present in the target fabrication facility. Tritium inventory estimates for IFE power plants using traditional targets range from 200 g to 4 kg, depending upon the fill method.[6] This range corresponds to activities of 7.1×10^{16} to 1.4×10^{18} Bq. Given that the tritium-lean targets would contain 100× less tritium than a traditional target, we expect tritium inventories in the target fabrication facility to be reduced by a similar factor. A reduction of the target factory tritium inventory to 2-40 g would significantly reduce its accident potential.

3.2 Waste hazards

The first wall WDR is dominated by similar, but not identical, isotopes due to differences in the neutron spectra between the two designs. In HYLIFE-II, ^{192s}Ir is responsible for 43% of the WDR, while ^{14}C and ^{59}Ni contribute 26% and 11%, respectively. In the tritium-lean design, ^{59}Ni is the single largest contributor at 41%. ^{14}C and ^{208}Bi contribute 39% and 9%, respectively. *Table II* gives values of the WDR for each of the key components.

Table II. WDR for key components.

Component	Volume (m^3)	Waste disposal rating HYLIFE-II	T-Lean
Coolant	1240	2.24e-3	3.32e-3
First wall	0.36	1.51e+0	2.40e-1
Second wall	3.93	2.09e-2	1.49e-3

4. Conclusions

The use of tritium-lean targets appears to have numerous S&E advantages over traditional target designs. Largest among these is the fact that the targets would be self-sufficient from a tritium point of view and the sizable reduction in the tritium inventory within the target fabrication facility. Other advantages include the freedom to select non-lithium bearing coolants and a reduction in the first wall damage due to attenuation/moderation within the target. All of these factors together with the belief that such targets may be viable at driver energies of 4-5 MJ due to the possible use of a fast igniter suggest that tritium-lean target designs, and the fast igniter, should be pursued in earnest.

Acknowledgments

Work performed under the auspices of the U. S. Dept. of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48 and Ministerio de Educación y Cultura, Spain, under Project DGCIT PB95-0230.

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