Fusion Reactor Design towards Radwaste Minimum with Advanced Shield Material

TOBITA Kenji, KONISHI Satoshi, NISHIO Satoshi, KOSAKO Kazuaki and TABARA Takashi
Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan
Sumitomo Atomic Energy Industries, Ltd., Tokyo 130-0026, Japan

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Abstract
A new concept of fusion reactor design is proposed to minimize the radioactive waste of the reactor. The main point of the concept is to clear massive structural components located outside the neutron shield from regulatory control. The concept requires some reinforcement of shielding with an advanced shield material such as a metal hydride, detriation, and tailoring of a detrimental element from the superconductor. Our assessment confirmed a large impact of the concept on radwaste reduction, in that it reduces the radwaste fraction of a fusion reactor A-SSTR2 from 92wt.% to 17wt.%.

Keywords:
radwaste, metal hydride, reactor design, shield, tokamak reactor

1. Introduction
In the conventional fusion reactor design, the neutron shield is used to protect the Super-Condacting (SC) magnets to function normally during operation, where the shield thickness is determined by irradiation properties of SC magnets such as the tolerable absorption dose of insulator. The design provides a “minimum shield thickness”. The problem of this design is that a large amount of radwaste, exceeding 10,000 tons of low and medium level radwastes, will be left after the decommissioning [1]. Without a dramatic reduction of the amount, the disposal of radwaste would be a critical issue impeding the extensive introduction of fusion energy. In this Letter, we describe the feasibility of a reactor design concept focusing on radwaste.

In the new design concept proposed here, the role of shielding is to protect outer structural materials from serious activation, which can lead to a dramatic reduction of radwaste. In this sense, it can be dubbed the “radwaste minimum” concept. On the basis of the clearance limit prescribed for a fission reactor [2], our preliminary assessment indicates that 83wt.% of the structural materials of a tokamak reactor will be cleared from regulatory control.

2. Details of the “Radwaste Minimum” Concept
We assume that criteria for a fission power plant are applicable to classify wastes from a fusion reactor. According to the criteria, the waste categorized as Low Level Waste (LLW) can be disposed of by shallow land burial; for that labeled as Medium Level Waste (MLW), waste management by deep geological reposition is required. Relating to the classification relevant in Japan, MLW corresponds to “high-βγ low level” waste, and LLW includes “low level” and “very low level” wastes. Clearance waste, regarded to have negligible waste hazard, would qualify for disposal as the waste exempted from regulatory control.

Table 1 lists the wastes at 50 years after the
decommissioning of a fusion power reactor A-SSTR2 [3] operated for 30 years at a neutron wall loading of 6 MW/m². The blankets and TF coils are dominant radwaste. The blankets are composed of replaceable and permanent portions, and the replaceable blankets are changed over every 2 years, amounting to 3,690 tons in 30 years. To generate a high toroidal magnetic field of 23 T (11T on the plasma axis), A-SSTR2 adopts a high-temperature SC with accompanying robust and massive coil cases. An important point read from Table 1 is that significant parts of radwaste originate from the outside of the neutron shield, as is common in the present fusion reactor design. Therefore, clearing the out-shielding components from regulatory control has a tremendous impact to a reduction of radwaste, leading to a "radwaste minimum" concept, which can be realized by the following measures.

(1) Reinforced shielding with an advanced shield material

Several metal hydrides can be regarded as advanced shield materials being capable of shielding neutrons more efficiently than the conventional shield materials such as steel plus water, polyethylene ((CH2)n) and B4C. Table 2 indicates several metal hydrides and their properties; the values in the table are reference-dependent, though. It is notable that some of the hydrides show higher hydrogen content than solid hydrogen and (CH2)n. Such hydrogen-rich materials should work as moderators of fast neutrons, decreasing neutron flux. Figure 1 shows the attenuation of neutron flux by various shield materials, which is calculated with the ANISN code [4] for a simplified geometry consisting of plasma, a blanket, a shield and a wall. VH2, TiH2 and ZrH2 show superior shielding capability to the conventional shield materials. Thus, using any of these advanced materials, one can reinforce the neutron shielding with a minimal change of reactor size.

![Fig. 1 Calculated attenuation of neutron flux for various shield materials.](image)

Although HfH2 can be another useful shield material, the calculation was not carried out because the cross section was not encompassed in ANISN.

(2) Removal or reduction of a detrimental element from TF coils

The present Bi high-temperature SC is produced by an ample use of Ag, convenient to laminate a Bi compound and form SC tape in the PAIR (pre-annealing and intermediate rolling) process [5] and to assemble the tape-shaped conductors in a wire. However, Ag is a detrimental element producing 108mAg with a lifetime of 127 years and thus it must be replaced by a low activation element for radwaste reduction. The new design concept assumes that Ag will be replaced by any other element suffering no significant activation. To add for information, niobium SCs (NbTi, Nb3Sn and Nb3Al)
widely used for fusion, whose magnetic field is too small to use for the TF coils of A-SSTR2 yet, are also problematic due to production of long-life $^{94}$Nb ($T_{1/2} = 2 \times 10^4$ years).

(3) Detriation

Prior to the storage in the interim facility, tritium concentration in the waste should be lowered substantially by heating or a photochemical process.

As reported previously [6,7], isotope tailoring and a reduction of detrimental impurities in structural materials are effective to lower the level of induced activation. Currently available SiC/SiC contains $^{14}$N, being crucial for waste management because of $^{14}$C ($T_{1/2} = 5,730$ y) produced by $^{14}$N(p,$\alpha$)$^{14}$C. Aside from the “radwaste minimum” concept, we assume that $^{14}$N-tailored SiC/SiC will be industrially available in future: Yet, $^{14}$C will be still produced in SiC/SiC by the (n,$\gamma$) reaction of $^{13}$C having the abundance of 1.1%.

3. Radwaste from A-SSTR2

By applying the “radwaste minimum” concept to A-SSTR2, we assessed the radwaste for the radial build shown in Fig. 2. Differences between the original A-SSTR2 design and the “radwaste minimum” concept are as follows:

1) The “radwaste minimum” design adopts VH$_2$ neutron shield with thickness of 78 cm and 77 cm on the inboard and outboard sides, respectively. The original design uses the 64 cm-thick and 54 cm-thick shield of TiH$_2$ on the inboard and outboard sides, respectively. Note that A-SSTR2 originally adopted a metal hydride (TiH$_2$) to lessen the shield thickness. Openings in the radial build of the original A-SSTR2 accepts the increase in shield thickness for “radwaste minimum” without changing the plasma size:

2) The “radwaste minimum” concept assumes to replace Ag of TF coils with a low activation material. On the other hand, the original design assumes to use Ag as much as the present product (~7 x 10$^{21}$ atoms/cm$^3$).

In the assessment of the wastes from both designs, the following hypotheses are posed:

1) Neglect $^{14}$N in SiC/SiC but, for the other structural materials, assume reasonable element compositions (including impurities) on the available product basis:

2) Tritium retained in waste is removed by detriation:

3) To reduce radwaste from the neutron shield, the shield material (TiH$_2$ and VH$_2$ in the conventional and new concepts, respectively) is segregated from the container (SiC/SiC):

4) A-SSTR2 operates at the fusion power of 4.5 GW and the neutron wall loading of 6 MW/m$^2$ for 30 years (availability of 80%), and it is disposed of after 50-year cooling.

Reinforced shielding of A-SSTR2 in Fig. 2 leads to an increment in weight of 1,140 tons. The level of induced activation of waste is calculated using a DCHAIN-SP 2001 code [8], provided with the FENDL/A-2.0 library (partly modified). The calculation is based on the one-dimensional modeling. The induced activation of the poloidal field coils and cryostat is estimated using the neutron spectrum at the surface of the outer vacuum vessel.

Figure 3 shows the clearance index for both designs and radionuclides critical to meet the clearance limit, where the clearance index represents the ratio of the level of induced activation to the clearance limit. Impact of the new concept on the out-shielding components is apparent. Table 3 shows the waste from A-SSTR2 for the conventional and “radwaste minimum” concepts. Of importance is that 83.2 wt.% of waste, corresponding to the shield and the outer structural components, would qualify for disposal as clearance waste when the new

<table>
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<th>coil case</th>
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<tr>
<td>TF coil</td>
<td></td>
</tr>
<tr>
<td>vacuum vessel</td>
<td></td>
</tr>
<tr>
<td>shield</td>
<td></td>
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<tr>
<td>permanentblk</td>
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<td>replaceableblk</td>
<td></td>
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<td>stabilizing shell</td>
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Fig. 2 Radial build of the fusion reactor A-SSTR2 based on the new concept.
concept is adopted. The detrimental elements of the LLW and MLW are \(^{10}\)Be, \(^{14}\)C and \(^{26}\)Al. These are mainly produced by nuclear reactions of key elements composing the blanket; \(^{6}\)Be(n,\(\gamma\))\(^{10}\)Be, \(^{11}\)B(n,\(\gamma\))\(^{11}\)Be, \(^{12}\)C(n,\(\gamma\))\(^{12}\)C, \(^{12}\)C(n,\(\gamma\))\(^{13}\)C, \(^{27}\)Si(n,\(n\)p)\(^{27}\)Al, \(^{28}\)Si(n,\(n\)D)\(^{27}\)Al, and \(^{27}\)Si(n,\(n\)D)\(^{27}\)Al. Figure 4 shows a comparison of waste normalized at 1 GWe for several fusion reactors. Radwaste production in the A-SSTR2 based on the radwaste minimum concept is a factor 5 to 10 lower than that in the other tokamaks. The main portion of MLW in the A-SSTR2 is the replaceable blankets, which can be reduced by recycling Be and Li.

Fig. 3 Clearance index for the conventional and proposed designs, and radionuclides critical to meet the clearance limit.

Table 3 Wastes of A-SSTR2 based on the conventional and new design concepts

<table>
<thead>
<tr>
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<th>Conventional Concept</th>
<th>New Concept</th>
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<tr>
<td></td>
<td>Weight (t)</td>
<td>wt.%</td>
</tr>
<tr>
<td>LLW</td>
<td>13,798</td>
<td>49.7%</td>
</tr>
<tr>
<td>MLW</td>
<td>11,759</td>
<td>42.4%</td>
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<tr>
<td>Clearance</td>
<td>2,188</td>
<td>7.9%</td>
</tr>
<tr>
<td>Total</td>
<td>27,745</td>
<td>100%</td>
</tr>
</tbody>
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Fig. 4 Comparison of waste weight per 1 GWe output between fusion reactors based on the conventional design and the A-SSTR2 based on the "radwaste minimum" concept. The wastes in all reactors are assumed to be classified 50 years after the decommissioning.
4. Conclusions

The “radwaste minimum” concept of fusion reactor design is proposed to lead to a dramatic reduction of radioactive waste. The new concept considers that the role of a neutron shield is to keep the outer structural components from considerable activation, rather than to assure of SC magnets to function during discharges. The presented concept requires some reinforcement of shielding with a minimal change of reactor size, which can be met by the use of an advanced shield material such as a metal hydride. An estimate based on the concept indicates that the radwaste from A-SSTR2 can be as low as 17wt.%, whereas the radwaste expected in the conventional way amounts to 92wt.%. The development of a low activation superconductor and the shield with a metal hydride is encouraged to make the concept feasible.

References