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Tritium issues to be solved for establishment of a fusion reactor

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ABSTRACT

In order to establish a D–T fusion reactor as an energy source, economical conversion of fusion energy to electricity and/or heat, attaining enough margins in tritium breeding, and insuring tritium safety must be simultaneously achieved. Scientists and researchers working on Tritium in Japan are now tackling with T related problems. Their research subjects can be categorized into two, i.e. researches on "Science and technology" to establish safe and economic Tritium fuel cycle for fusion reactors and "Tritium safety". Many researchers from various universities, and institutes such as NIFS, JAEA and IEA (Inst. Environmental Science) in Japan are involved in various research programs. In this report, after brief introduction on Tritium related researches in Japan, important T issues to be solved for establishment of a fusion reactor will be summarized considering the handling of large amount of tritium, i.e. fuelling, D–T burning, T inventory, exhausting, refinement, confinement, permeation, leakage, contamination, regulation and tritium accountancy.

1. Introduction

Radioactivity and limited resource of Tritium concern us for establishment of a fusion reactor as an energy source. For a D–T fusion reactor to be an energy source, economical conversion of fusion energy to electricity and/or heat, with enough margin in tritium breeding, and insuring tritium safety, must be simultaneously achieved. In particular, handling of huge amounts of tritium in a reactor system needs significant effort [1–3] to ensure that the radiation dose of radiological workers and of the public is below the limits specified by the International Commission on Radiological Protection (ICRP).

Unfortunately tritium resources are very limited. Fig. 1 shows the natural abundance of tritium [4], which is generated by cosmic rays and also by nuclear reactions (atomic bombs and nuclear reactors) after the 2nd world war, is very small as shown in the figure. Therefore tritium should be artificially produced. Not only for the safety reasons but also to avoid the shortage of tritium resources, tritium inventory in a reactor must be kept as small as possible and the tritium breeding should have enough margins to compensate the inventory in all tritium systems including the reactor vessel and pumps, and the loss due to tritium decay of around 5%/year.

Tritium is easily detected by β-electron counting with detection limit and/or accuracy of several Bq/cm^2 on solid surfaces and around 0.1 Bq/cm^3 in water. However, the β-electron counting is limited to below 10^9 Bq or mg order of T. For much larger amount of tritium, mass and/or pressure measurements, the same way to measure other hydrogen isotopes, are employed. The measurement of decay heat allows calorimetry but its accuracy is only 10^{-2} to 10^{-3}. All present tritium measurements except β-counting give only 3–4 digit accuracy and any loss of tritium less than 0.1% is hardly possible to detect. Since public exposure to tritium is regulated at a level as tiny as a few Bq/cm^2, tritium must be strictly confined in handling systems.

In this report, after brief introduction on tritium related researches in Japan, important T issues to be solved for establishment of a fusion reactor will be summarized considering the handling of large amount of tritium, i.e. fuelling, D–T burning, T inventory, exhausting, refinement, confinement, permeation, leakage, contamination, regulation and tritium accountancy.

2. Tritium related researches in Japan

Tritium researchers in Japan are now tackling with T related problems and their research subjects can be categorized into two: (1) "Science and Technology" to establish of safe and economic tritium fuel cycles for fusion reactors, and (2) Science and Technology for "Tritium Safety".

Researches on (1) "Science and Technology" have been carried out mainly in Japanese Universities and JAEA (Japan Atomic Energy Agency) under the project of "Tritium for Fusion (Tritium Science and Technology for a Fusion Reactor)" supported by Grant in Aid for Scientific Research, Ministry of Education, Culture, Sports, Science and Technology (MEXT), Priority area No. 467 (2007–2011) [5]. In addition, JAEA is doing its original research works mainly related to ITER [6]. Some works have also been done under the framework

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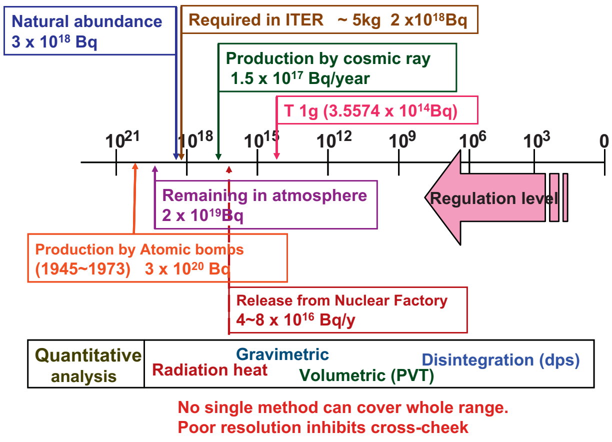

Fig. 1. Comparison of tritium amounts, resources, abundance and regulation. Methods for qualitative analysis are also given [4].

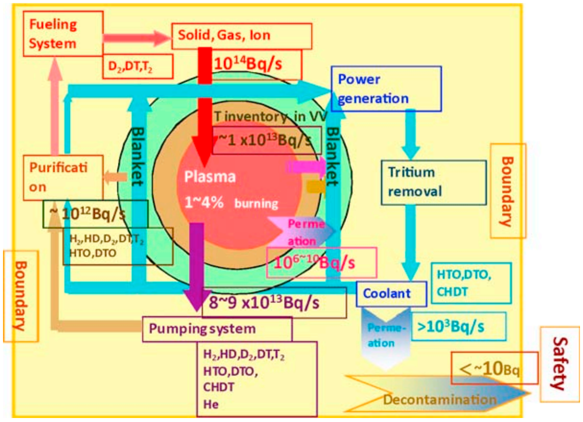

Fig. 2. Amounts of fuel flowing in a tritium recycling systems [8].

of NIFS-LHD (National Institute for Fusion Science-Large Helical Device) collaborations through Toyama University.

The main aim of the project "Tritium for Fusion" is to establish tritium safety in a D–T fusion reactor. Since huge amounts of radioactive tritium must be used as a fuel, lots of safety concerns are newly appearing to be solved. They are tritium safeties in (i) fueling systems keeping continuous D–T burning, (ii) tritium exhausting, recovering and refining processes, (iii) tritium breeding systems with a breeding rate over 1.05, and (iv) tritium monitoring and accounting systems. In addition, easy isotopic exchange reactions of tritium with ubiquitous hydrogen in water and hydro-carbons result in the contamination of the systems, which require decontamination. The project also aims to provide new insights into basic tritium science and technology and to encourage young scientists.

Researches on (2) "Tritium Safety" have been carried out mainly under the framework of LHD Project Research Collaboration of NIFS. Detailed subjects are:

2.1. Behavior of tritium in environment (mainly for Nuclear reactors) including: (i) water analysis (rain, river, groundwater, etc.), (ii) organic bonded tritium (OBT) behavior (measurement, incorporation), (iii) modeling (water, air, OBT, dose) and (iv) atmospheric analysis (chemical forms)

2.2. Studies on biological effects including: (i) establishment of a hypersensitive assay system that can be applied to experiments in radiation biology (cultured cells, transgenic mice), (ii) biological responses to low-dose (rate) tritium radiation, especially to tritiated water (HTO) exposure, and (iii) molecular mechanisms of DNA damages and repair.

Many researchers from various universities, and institutes such as NIFS, JAEA and IEA (Inst. Environmental Science) in Japan are involved in the research programs given above. Most of their recent results are presented in 46 papers in 9th International Conference on Tritium Science and Technology, Nara, Japan, Dec. 2010) [7], co-organized by the project "Tritium for Fusion" and NIFS, and 20 papers in this conference.

3. Fusion reactor system – a huge open T handling system

Fig. 2 is a schematic drawing of fuel flow in a fusion reactor with blanket systems to generate power and to breed tritium simultaneously, together with accompanied problems [8]. For safety reasons, tritium in a reactor will be limited to only a few kg orders in weight, with radioactivity up to 10^{17} Bq [9,10]. In the figure, fuel throughput is $\sim 10^{14}$ Bq/s, based on the maximum fuel throughput for one ITER discharge, 200 Pa m^3 ($\sim$2.5 g)/400 s. As discussed later, fuel burning efficiency is likely to be 1–4%. In addition, deposited layers formed on plasma facing surface and shadowed area retain large amount of fuels with a fuel retention rate of $\sim$10% ($\sim 1 \times 10^{13}$ Bq/s) for full carbon first wall. Accordingly, most of the throughput fuel of 8–9 $\times 10^{13}$ Bq/s is exhausted and refueled after reprocessing (refinement and isotope separation). In blanket systems, $\sim 10^{12}$ Bq/s must be bred, because the amount of bred T must exceed that of burned T. There are two boundaries one between the vacuum vessel (or reactor) and the blanket (or tritium processing) the systems and the other between the tritium processing system and the environment. Between the boundary, T is transferred either by permeation and leakage and/or cross contamination. Since public exposure to tritium is regulated at a level as tiny as a few Bq/cm^2, tritium must be strictly confined in a reactor system with accountancy of an order of pg (pico-gram). Considering the through-put of 10^{17} Bq, each boundary should reduce T level by orders of 10^8.

We are facing to lots of safety concerns in the handling of huge amounts of tritium as a fuel and being bred in a blanket. Passive barriers consisting of process piping, jacketed vessel, guard or second barrier piping are taken into account in the ITER tritium systems [10]. The decommission factor (DF) of 10^{-8} seems hardly possible by a single step. For example, tritium permeation barrier has been extensively studied, but only reduction factor of 10^{-3} is reliable. Generally qualitative analysis with the accuracy of more than 3 orders of magnitude is hardly possible. Therefore the loss of 10^{-3} is out of accountancy in higher T handling side, while the leakage of this amount through the boundary to the lower T handling side cannot be accepted, so as the cross-contamination as evidenced in Fig. 3 [4]. The figure shows a good example indicating how tritium is transferred by cross-contamination. Gloves as essential equipment in a tritium handling system are always contaminated and tritium on the glove surface is immediately transferred to non-contaminated materials. The cross contamination is caused by easy replacement of T with the ubiquitous lighter hydrogen isotopes like protium (H)/deuterium (D) in water and hydrocarbons in the atmosphere. The consequence is multi-stage contamination and sequential reduction of the contamination by second and third gloveboxes might not work.

The easy isotopic replacement results in additional problems for T permeating through process piping. The permeated tritium readily reacts with surface contaminants to produce hazardous tritiated water and/or hydrocarbons. In particular, ferrite, a low activation structure candidate material, has very high tritium permeability and needs permeation barrier with the permeation reduction of 5–6 orders of magnitude which is not attained yet. For a water cooling system, permeated tritium from the plasma facing surface or blanket to the coolant water easily produces HTO, resulting in