Expiratory Testing as a Simple and Effective Bioassay Method for Screening Workers for Tritium Exposure in Fusion Test Facilities

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This study evaluates expiratory testing as a simple bioassay method for estimating the effective dose equivalent for individuals working inside radiation control areas in a large helical device (LHD) building at the National Institute for Fusion Science (NIFS) in Toki City, Japan. The expiratory testing apparatus is configured according to similar devices reported previously. The core components of the apparatus include the sample collection device, a water bubbler column, exhalation airflow controls, and a solution injection component. Exhaled water vapor from individual test subjects is collected and tritium levels are measured using a liquid scintillation counter. Tritium radioactivity measurements are then compared to the effective dose according to evaluation criteria estimated using the effective dose equation for tritium.

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The large helical device (LHD) was constructed in 1998 at the National Institute for Fusion Science (NIFS) in Toki City, Japan [1] and is one of the largest magnetically confined heliotron-type plasma experiment devices [2]. The deuterium plasma experiment (D-D experiment) is an advanced project that was conducted at the LHD facility to investigate high-performance plasma and the behavior of hydrogen isotopes [3]. In D-D experiments, tritium and neutrons are produced via D-D reaction in deuterium plasma. A portion of the generated tritium with a maximum energy of 1.01 MeV remained inside of vacuum vessel; then, the tritium is placed in the plasma-facing components. Accordingly, tritium requires careful handling to reduce the risk of its release into the surrounding environment, although the amount of tritium production is low.

After these experiments, maintenance workers must enter the vacuum vessel that is located inside the LHD’s radiation control area. Thus, measuring and monitoring the worker’s radiological exposure in relation to the effective dose for tritium for these workers is critical for protection of human health. An individual’s internal radiation exposure is routinely monitored at tritium handling facilities [4] and is often accomplished by analyzing excretory fluids in the form of a bioassay test that effectively assesses the internal dose rate [5–7]. For example, tritium measurement in urine is a common method to evaluate the effective dose equivalent for workers [5]. However, this method is not ideal due to complex pre-treatment requirements associated with testing and sufficient time is required to collect data for assessing the effective dose for tritium [4, 8].

It is assumed that ingested tritium soon reaches equilibrium in bodily fluids depending on metabolism and is distributed uniformly in all forms of soft tissue [9]. When tritium is present in the human body, a portion of it is discharged as exhaled water vapor during respiration [10]. Therefore, expiratory testing is often used at tritium handling facilities as a simple bioassay method [11–13]. This method is simple and provides data faster than conventional urine testing methods, and the results can be used to estimate the internal dose rate of tritium.

Our radiation control group performed the expiratory testing method using an integrated water bubbler for the dose assessment of workers according to the NIFS safety management plan [14]. The water bubbler device was configured according to the guidelines established by the Japan Atomic Energy Agency (JAEA) for such devices [11]. This study examines the effectiveness of our novel expiratory test device for LHD deuterium plasma experiments and estimates the effective dose equivalent of tritium with respect to human exposure.

Figure 1 shows the components of the expiratory test apparatus using water bubbler. The apparatus comprises an exhaled air sample collection component, a water bubbler column that uses an Allihn type condenser without cooling water, airflow rate controls comprising a dry gas meter (DCDA-5C, Shinagawa Corporation, Japan) and digital display, and a solution injection component (Fig. 2). It is a semi-automatic device controlled by a programmable logic controller (PLC), and the device status and sequence data are displayed on the front control LCD touch panel connected to the PLC. Before conducting an expiratory test, the individual administering the test places the distilled wa-

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and liquid scintillator inside the apparatus and activates
the heater of the solution injection component (40°C) to
prevent water vapor condensation in the expiratory injec-
tion line. The administrator must remove any air bubbles
observed inside the distilled water tube by manual adjust-
ment of valves and the liquid feeding pump.

Once the administer renders the device ready to accept
the sample, the test subject places a 20-mL vial in the sam-
ping vial box, where an optical sensor detects the vial and
proceeds to the next step. The subject then connects the
mouthpiece (HC-21MP, TANITA, Japan) to the tip of the
inlet tube and pushes the start button on the touch panel.
Once activated, the vial box moves under the water bub-
bler column and 5 mL of distilled water is injected into the
water bubbler chamber. The volume of exhaled air sent to
the bubbler column is adjustable; herein, it was set to 10 L.
The instructions on the touch panel prompt the subject
to breathe into the mouthpiece until 10 L of air are exhaled
into the bubbler column, while taking care to maintain a
low exhalation rate as a precaution against water bubbling
over the edge of the Allihn type condenser. The exhaled
water vapor containing tritium is trapped in the distilled
water. When exhaled air reaches 10 L, a buzzer sounds to
indicate the end of the sampling. The valves are closed,
and the bubbled water is dropped into a 20-mL polyethy-
lene vial. The bubbler column is then flushed using 5 mL
of distilled water that is also dropped into the polyethy-
lene vial, and fresh air flushes the bubbler column for a
few minutes to collect any residual drops of water. Herein,
the standard deviation of recovered water volume was 0.4
(n = 9). Once the sample is collected, 10 mL of liquid
scintillator is added to the vial. Finally, the bubbler col-
umn is washed with 5 mL of distilled water and then air
flushes out the column for a few minutes to reduce resid-
ual tritium contamination to minimize the so-called “mem-
ory effect.” 10 mL of liquid scintillator (Ultima Gold LLT,
PerkinElmer, USA) was added and mixed with the sample
manually. After preparing the sample vial, the radioac-
tivity of tritium was measured using a liquid scintillation
counter (Tri-Carb4910TR, PerkinElmer, USA) for 50 min
(10 min × 5 repeats). Counting efficiency values were de-
termined using a standard tritium solution (SRM 4361C,
NIST, USA). The background counting rate in counts per
minute ranged from 3 - 5 cpm, with a mean value of 4 cpm.
Figure 3 schematizes the testing process.

The method of internal dose assessment was previ-
ously reported [9, 12, 15], and the effective dose (E_d: μSv)
for tritium is estimated using the following equation:

$$E_d = \frac{A_T}{V_W \times C_{eff}} \times B_W \times C_F,$$

Fig. 1 Core components of expiratory test device.

Fig. 2 Outline of expiratory test device.
where $A_T$ is the tritium amount in exhaled water vapor collected by the water bubbler (Bq), $V_W$ is the average amount of water vapor contained in 10 L of exhaled air, $C_{eff}$ is the collection efficiency of exhaled water vapor sent to the water bubbler, $B_W$ is the water content of the reference man, $C_F$ is the dose coefficient of workers for inhalation of tritiated water ($1.8 \times 10^{-5}: \mu$Sv/Bq) [16].

A $V_W$ of 0.38 g was used in accordance with results of a previous study [12]. Tsujimoto et al. reported that the collection efficiency of exhaled water vapor ($C_{eff}$) ranges from 85% to 96% [12]; therefore, we used $C_{eff}$ value of 0.85. The International Commission on Radiological Protection (ICRP) recommends using a $B_W$ value of 42,000 g for the Caucasian Reference Man (CRM) [17]. Given that the average physical size of the Japanese male is slightly less, a value of 37,000 g was used to represent the Japanese Reference Man (JRM) [18]. As mentioned previously, the average background counting rate was measured inside the control area and ranged from 3 - 5 cpm. Therefore, the detection limit was set under 5 cpm.

The evaluation criteria are listed in Table 1. If a subject’s test results indicated a count rate > 100 cpm (Judgment C in Table 1), the result must be verified using a bioassay test such as the urine testing method. The methodology and apparatus described in this paper are currently used to protect workers from radiation exposure risks at the LHD at the NIFS.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Count per minute (cpm)</th>
<th>Effective dose: µSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND</td>
<td>&lt; 5</td>
<td>Not detected</td>
</tr>
<tr>
<td>A</td>
<td>5 ~ 10</td>
<td>0 ~ 1</td>
</tr>
<tr>
<td>B</td>
<td>10 ~ 100</td>
<td>1 ~ 10</td>
</tr>
<tr>
<td>C</td>
<td>100 &lt;</td>
<td>Require re-examination</td>
</tr>
</tbody>
</table>

Table 1 Management criterion of expiratory test with count rate from the liquid scintillation counter and decision criteria.

![Flowchart](Start.png)

Fig. 3  Schematic of expiratory testing process.

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