Radiation hazards in PF-1000 plasma generator fusion research (part 2)

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Received: 26 March 2015 / Published online: 26 May 2015
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Abstract This paper focuses on radiation exposures to researchers and technicians involved in fusion research. It is the second article in the series on this topic. It discusses immediate exposures to the ionizing radiation that is generated immediately during fusion research performed on the PF-1000, a dense magnetized plasma generator that is the world’s largest.

Keywords Nuclear fusion · Health physics · Radiation protection · Radiometry

Introduction

The next few decades will be characterized by rapid development of nuclear fusion programs and, it is hoped, their application to power production. Large plasma facilities, such as the Join European Torus (JET) tokamak, the Wendelstein 7-X (W7X) stellarator, the International Thermonuclear Experimental Reactor (ITER) tokamak, and the Demonstration Power Plant (DEMO), have employed programs for radiation protection that have been approved by the national as well as European authorities. Many types of plasma facilities are operated worldwide to conduct plasma research for fusion development. In Poland, most plasma research is performed at the PF-1000 facility, the world’s largest z-pinch machine. The Polish National Atomic Energy Agency (PNAEA) classified the PF-1000 device as a particle accelerator. Additionally PNAEA has declared that the PF-1000 facility does not represent a radiation hazard to workers or the environment.

From the beginning of operation in 2001 up to the present time, a system for minimizing exposure from neutrons has been implemented. This system consists of movable paraffin wax panels that shield the locations, i.e., the steering room and other locations in the research suite, that are accessible to workers during the plasma discharges.

The immediate ionizing radiation that accompanies fusion reactions has a very wide energy range and different origins. Some are blocked by the vacuum vessel walls and the metal that covers the paraffin panels. However, small releases of high-energy gammas freely penetrate the environment.

Among the types of radiation that accompany the synthesis of deuterium (see Eqs. 1–3), neutrons and X-rays and gamma radiation are the most penetrating species generated. They are emitted from the plasma focus and the vacuum chamber. The level of exposure to personnel has not been completely investigated.

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\[ D + D \rightarrow ^{4}\text{He} + \gamma(23.8 \text{ MeV}); R_a \approx 10^{-5}\% \]  

where \( R_a \) = reaction abundance.

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emission of ionizing radiation that is the result of nuclear decay following neutron activation, and its expression of the radiometric data in terms of effective dose. We also confirmed the effective discrimination of the neutron component of radiation by the instrument. In this paper we show the exposures measured from the PF-1000 device with the RSS-131 ionization chamber during a recently completed experimental deuterium procedure that allowed effective dose assessment for the personnel present during experiments.

Materials and methods

The PF-1000 device

The plasma-focus (PF-1000) device is operated in the Institute of Plasma Physics and Laser Microfusion (IPPLM). During an experimental procedure the vacuum vessel is filled with deuterium and high-current discharge induces the deuterium to enter the plasma state. Deuterium nuclei begin to fuse, but most of them undergo reactions beam target. This results in the production of neutrons and ionizing radiation that leave the vacuum vessel. Usually up to twenty discharges are fired every day. The experimental procedures effectively run over a period of months, up to 6 months. A detailed description of the PF-1000 device, as well as the phenomenon of plasma formation, can be found in our recent reports [2, 3].

The same group of personnel are involved in preparation and setup of the experimental procedures. This is the critical group as defined by the International Commission on Radiological Protection (ICRP) [4] and is intended to be representative of persons employed at IPPLM who are expected to receive the highest doses of radiation. Other researchers that conduct their own experiments join this group incidentally. During a particular discharge, all personnel are confined to the steering room. An exception is anyone whose presence outside of the steering room in the research suite is necessary, but these cases are very rare.

In recent years, various methods were used to measure the radiation hazard caused by plasma research. Personnel were issued individual dosimeters equipped with film, or thermoluminescence dosimeters (TLD). In addition, ionization chambers were stationed in different positions across the experimental facility to record during discharges. These devices were used incidentally and usually temporarily. Currently, personnel exposure is monitored by TLD dosimeters worn by two technicians. Up until the present, neither individual dosimeters nor the ionization chambers have registered a radiation dose exceeding the prescribed limits to personnel. It is worth nothing that the apparatus we use for investigation of basic physical phenomena are not sufficient for human exposure assessment. However some of the abovementioned methods such as TLD [5, 6] are employed in both categories of measurement.

The ionizing radiation component of D–D fusion

The radiation accompanying all plasma discharges includes 24 MeV gammas generated during D–D fusion reactions (Eq. 3), whose measurement is a radiometric challenge. The dense deuterium plasma itself is a strong source of ionizing radiation, mainly X-rays [7, 8]. Charged particles, mainly electrons, due to their interactions with the copper anode, are the source of secondary Bremsstrahlung radiation. The X-ray diagnostics, which are established for collection of qualitative information regarding impurities, are not geared towards estimating radiation hazards from plasma-particle interactions.

The neutrons released from the plasma focus that escape the vacuum vessel pass through the surrounding environment. They undergo many different nuclear reactions. The radiative capture: \( n, \gamma \) is the most common and likeliest nuclear reaction. Other reactions: \( n, n'; n, p; n, d; n, x \) occur with lower probability. The nuclei that are the targets of the abovementioned nuclear reactions are excited and generate ionizing radiation. As a result, there is a bimodal time scale of ionizing radiation emission. The immediate (prompt) emission of gamma rays manifests after nuclear reactions that lead at once to the production of mostly stable nuclides. The delayed gamma emissions that are mainly the result of neutron activation of metals that are in the vacuum vessel can last up to hundreds of years [9, 10].

The challenge of personnel monitoring in this environment is due to the very broad energy scale that ranges from a few keV to almost 24 MeV, and also the wide timescale that ranges from nanoseconds to hundreds of years. This paper is a continuation of our recent studies on the applicability of the RSS-131 ionization chamber to this unique situation [1].

Radiation dose monitoring by means of RSS-131 high efficiency ionization chamber

The RSS-131 ionization chamber has been designed with the intention of measuring ultra-low values of gamma radiation in the neighborhood of 71.7 fA kg\(^{-1}\) (1 \( \mu \)R h\(^{-1}\)) with an accuracy of up to 95%. Its construction and characteristics both have been the subject of many reports and publications [11, 12]. Its application in radiation measurements in a pulsed mixed radiation field \( n + \gamma \) that is the result of D–D fusion is a completely new challenge. Our recent work [1] proved the applicability of this instrument in dose rate measurements during fusion.
procedures. The completed calibrations revealed its accuracy for gamma radiation with an ultra-broad time scale (from ns up to hundreds of years).

RSS-131 ionization chambers have been placed in four characteristic locations that are permanently (position \( j = 1 \), steering room, position \( j = 2 \), visitors’ room) or intermittently (position \( j = 3 \), Faraday cage, position \( j = 4 \), assembly hall) occupied by researchers and facility staff. The most important among them is the steering room, due to the fact that all those involved in procedures spend time in it.

**Radiometer measurements during plasma discharges**

The contribution to the dose of ionizing radiation by a particular pulse is reflected in the indication curve recorded by the RSS-131 ionization chamber. A series of five peaks registered during five respective discharges from #9955 to #9959 is presented in Figs. 1 and 2. The peaks that were registered by the radiometers in the other positions had a similar shape.

The pulses recorded by radiometer were the subject of interpolation. The log-normal function described by Eq. 1 most closely fitted the experimental data:

\[
\hat{X} = A \times \frac{e^{\left(\frac{-\mu}{2\sigma}\right)^2}}{2 \times \pi \times x \times \sigma},
\]

where: \( A, \mu, \) and \( \sigma \) are fitting parameters.

The amplitude of impulse \( X_{\text{Max}}^{j,i} \) that was registered by the radiometer in the \( j \)th position during the \( i \)th plasma discharge was considered the crucial parameter.

**Fig. 1** Printout from the screen of the RSS-131 ionization chamber. The row of pulses represents emissions of ionizing radiation that accompanied a series of plasma discharges (#9955–#9959) registered in the steering room. The radiometer records in non-SI units: 1 \( \mu \text{R} \, h^{-1} = 71.7 \, \text{fA} \, \text{kg}^{-1} \)

**Fig. 2** The discrete representation of the row of pulses presented in Fig. 1. 1 \( \mu \text{R} \, h^{-1} = 71.7 \, \text{fA} \, \text{kg}^{-1} \)

**Correlation between radiometer measurements and total neutron yield**

Measurements from the steering room, subject to the most exposure, were used. The amplitude of each pulse was plotted against total neutron yield \( Y_n^i \) measured during the \( i \)th plasma discharge by a silver activation counter (SAC) [3], revealing a linear relationship. From this relationship, it may be assumed that ratio of \( Y_n^i \) to the intensity of the ionizing radiation is almost constant for a particular position; however, it is actually position-dependent. Based on an interpolation formula for the indications obtained from measurements inside the steering room and the results of measurements in other positions and the assumption mentioned above, it is possible to make appropriate extrapolations. They are expressed by Eq. 5,

\[
W_j = \frac{X_{\text{Max}}^{j,i}(Y_n^i)}{X_{\text{Max}}^{j,i}(Y_n^1)},
\]

where: \( W \) is the extrapolation coefficient, \( j \)-th is the location of the measurement (\( j = 1 \)–4) where \( j = 1 \) is the steering room, \( X_{\text{Max}}^{j,i}(Y_n^i) \) is the maximum value of the dose rate that was registered at the \( j \)th position for the \( i \)th plasma discharge, \( Y_n^i \) is the total neutron yield during the \( i \)th discharge (based on SAC measurements), and \( X_{\text{Max}}^{j,1}(Y_n^1) \) is the maximum value of the dose that was registered at position 1 based on interpolation made for the results obtained in the steering room. The extrapolation factor changes by a factor of 20 between different places inside the experimental suite.

**Estimation of exposure for a given plasma discharge**

The results of the measurements performed (during the \( i \)th discharge in the \( j \)th position) by the radiometer constitute
the indication curve. That curve is interpolated by the log-normal function and the main parameter of this interpolation is considered to be the function’s amplitude $\bar{X}_{\text{Max}}$. The amplitude depends on three other parameters: exposure duration given by the coefficient $C(t)$, the energy of the radiation represented by relative response of the radiometer $r$, and the ambient dose equivalent rate $H^*(10)^{j\text{th}}_n$ from the neutron radiation. All of those can be expressed by the following formula:

$$X^{ij} \sim \bar{X}_{\text{Max}}^{ij} (C(t), r, H^*(10)^{ij}_n).$$

Assuming that for a broad energy range the response of the radiometer is close to $r = 1.0$, the following equation results:

$$X^{ij} = \left(\bar{X}_{\text{Max}}^{ij} \times C(t') \times t'\right) - \left(S_n \times H^*(10)^{ij}_n\right).$$

This is the formula that is used to express the so-called “true value” of the exposure rate corresponding to the $i$th discharge in the $j$th position registered by the RSS-131 ionization chamber. The quantity $H^*(10)^{ij}_n$ used in both formulae represents the extrapolated value of the ambient dose equivalent. It was evaluated based on a series of measurements performed with a Bethold radiometer and correlated with the SAC measurements. The neutron radiation hazard is the subject of a separate study. Combining Eqs. 6 and 7, with the proven linear relationship between $Y_n$ and $X^{ij}_{\text{Max}}$, and considering the numerical values of $W$, it is possible to estimate the radiation dose from the immediate ionizing radiation emission. It can be calculated for each site in the experimental suite and each particular $j$th discharge as well. Formula 8 shows this dependence:

$$X^{ij} = \left(W^{ij} \times (A \times Y^{ij}_n + B) \times C(t') \times t'\right) - S_n \times H^*(10)^{ij}_n,$$

where: $A$ and $B$ are the coefficients of the linear equation that links $Y_n$ (total neutron yield) with the dose of ionizing radiation and the time duration of plasma discharge $t'$ ($t' = 200$ ns) [2], $C(t')$, the time response coefficient equal to $1.925 \times 10^8$.

### The annual effective dose assessment

The annual effective dose to a person involved permanently in plasma research conducted at the PF-1000 facility caused by the emission of ionizing radiation was calculated based on total neutron yield, $Y_n$. During the evaluation process, the relationship between neutron emission and the electromagnetic component was taken into consideration [13] in estimating the dose to the $i$th position in the experimental suite. For all considered positions, the relation between $Y_n$ and the dose equivalent was linear, however, the ratio between the ambient neutron dose and the electromagnetic radiation dose changed with different positions.

The annual exposure dose $X^{ij}_i$ was calculated based on the annual neutron budget; that is, the sum of neutrons emitted during all discharges fired during the experimental year.

For dose assessment, a realistic scenario of radiation hazard was implemented. That was based on the recorded neutron budget and the frequency of experimental procedures during the observed years of research.

The annual exposure dose for each position in the experimental suite has been recalculated and expressed as air kerma $K^{ij}_p$ and subsequently, effective dose equivalent $DE^{ij}_r$. The ICRP recommendation [14] has been a source of information regarding conversion coefficients $(k_{k,DE})$ used for the above calculations. The conversion of the air kerma to the effective dose equivalent was done based on the following formula:

$$DE^{ij}_r = 0.00877 \times X^{ij}_i \times k_{k,DE}.$$ (9)

where $k_{k,DE}$ is the mean value (0.749) for the conversion factor for electromagnetic radiation with an energy range of 0.06–20 MeV.

### Result

The ionizing radiation dose that is a component of human radiation exposure during the D-D research procedures was intensively measured from June 2013 till February 2014. This research was carried out in four different positions in the experimental suite. The blue line represents the annual effective dose limit for public exposure; the red line represents the annual effective dose limit for occupational exposure. There were no plasma experiments in 2007. (Color figure online)
2014, representing plasma discharges #9957–#10345. The resulting data were the subject of analysis and radiation dose assessment. The results of measurements were the subject of dose assessment after evaluation according to the calibration process [1] and Eq. (9). The final results are presented in term of effective dose in Fig. 3.

Conclusions

Both neutrons and ionizing electromagnetic radiation contribute to human radiation exposure during plasma research conducted using the PF-1000 facility. It is worth noting that the annual effective dose to the personnel involved in this research is a few μSv, i.e., it is within the dose limits approved by the Polish national authority [15]. Among the positions in the experimental suite, the Faraday cage is the most hazardous position due to its short distance from the device. The lowest radiation hazard is in the visitors’ room. The annual effective dose depends on the annual neutron budget since the dose from ionizing radiation depends on the number of emitted neutrons. Thus, the neutron budget for the PF-1000 device must be the subject of very careful planning.

The radiation hazard due to plasma research conducted at the PF-1000 facility will increase because of neutron activation of the vacuum vessel’s walls. This hazard will be due to increasing activities of $^{60}$Co and $^{59}$Ni.

Acknowledgments This work was partly supported by the IAEA CRP RC-16956 and RC-17165 Grants as well by the Polish Ministry of Science and Higher Education within the framework of the financial resources in the year 2014 allocated for the realization of the international co-financed projects.

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