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Original Article

Assessment of N-16 activity concentration in Bangladesh Atomic Energy Commission TRIGA Research Reactor

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ABSTRACT

An assessment for determining N-16 activity concentrations during the operation condition of Bangladesh Atomic Energy Commission TRIGA Research Reactor was performed employing several governing equations. The radionuclide N-16 is a high energy (6.13 MeV) gamma emitter which is predominately created by the fast neutron interaction with O-16 present in the reactor core water. During reactor operation at different power level, the concentration of N-16 at the reactor bay region may increase causing radiation risk to the reactor operating personnel or the general public. Concerning the safety of the research reactor, the present study deals with the estimation of N-16 activity concentrations in the regions of reactor core, reactor tank, and reactor bay at different reactor power levels under natural convection cooling mode. The estimated N-16 activity concentration values with 500 kW reactor power at the reactor core region was 7.40×10^5 Bq/cm^3 and at the bay region was 3.39×10^{-5} Bq/cm^3. At 3 MW reactor power with active forced convection cooling mode, the N-16 activity concentration in the decay tank exit water was also determined, and the value was 4.14×10^{-1} Bq/cm^3.

1. Introduction

The TRIGA Mark-II Research Reactor of Bangladesh Atomic Energy Commission (BAEC) attained its first criticality on 14 September, 1986. Since then it has been operating at different power levels for manpower training, various R & D activities, and radioisotope production [2]. Regulations of Bangladesh Atomic Energy Regulatory Authority require that nuclear reactor embark on all reasonable safeguards to protect the environment and the health and safety of persons, including identifying, controlling, and monitoring the release of nuclear substances to the environment [[3]]. All nuclear reactors have radiation protection programs intended to minimize worker and public exposure to radiation.

The BAEC TRIGA reactor is a research reactor having a maximum continuous thermal power output of 3 MW. The reactor has been designed for operation under three operation modes namely steady state mode, square wave mode, and the pulse mode. The steady state mode of operation could be performed under two cooling modes: (i) natural convection cooling mode (NCCM) and (ii) forced convection cooling mode (FCCM). The NCCM can be activated for a power level of up to 500 kW without primary cooling pump operation. During NCCM, heat generated in the reactor core is removed by the tank water through natural convection cooling mechanism [15]. In water-cooled reactor like BAEC TRIGA Research Reactor, the capture of fast neutrons by O-16 in the core water produces radioactive N-16, which decays with a very high energy gamma ray (6.13 MeV) but with a short half-life of 7.14 s [4]. To determine the N-16 activity concentration in the region of the reactor core, reactor tank, and reactor bay is important as the radioactive N-16 produced in the reactor core may rise to the pool surface and can be mixed to the bay region during normal reactor operation condition. For reactor operation at low power to the full power of 3 MW, FCCM can be activated which uses the primary and secondary cooling pumps. Heat produced during this mode of operation is dissipated into the atmosphere through a cooling system consisting of primary and secondary cooling loops Salam et al. [15]. During this operation mode the decay time is increased by means of a decay tank with internal baffles. The decay tank holds the coolant for approximately 143 s before the coolant reaches the primary pump room. Besides to ensure safety, the decay tank is covered with about 102 cm thick heavy concrete shielding to

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attenuate the high-energy gamma rays (6.13 MeV) being emitted by the N-16 nuclei [4].

In our previous study [3], an assessment was performed to estimate the activity concentrations and release rates for the airborne radioisotope Ar-41. Here, we estimated the activity concentration values for the short-lived high-energy gamma emitter N-16. In a previous work [GA [SAR [5]], limited study was conducted to determine the N-16 activity concentration in the decay tank exit water at 3 MW. In our present work, a detail study was carried out to estimate the N-16 activity concentrations in the regions of reactor core, reactor tank, and reactor bay at different reactor power levels under NCCM. Under FCCM, N-16 activity concentration in the decay tank exit water was also determined and verified at maximum reactor power of 3 MW.

2. Brief description of the BAEC TRIGA Research Reactor

The BAEC TRIGA Research Reactor is a light water-cooled, cylindrical shaped pool-type research reactor which uses uranium–zirconium hydride fuel elements in a circular grid array. The reactor uses low enriched uranium fuel with enrichment of 19.7% U-235, $ZrH_{1.6}$ (prime moderator), and burnable poison ^{167}Er. The core is situated near the bottom of water filled tank, and the tank is surrounded by a concrete bio-shield. The tank is made of special aluminum alloy and has a length of 8.23 m and a diameter of 1.98 m, filled up with 24,865 L of demineralized water [12]. The reactor core consists of 100 fuel elements (93 standard fuel elements, 5 fuel follower control rods, and 2 instrumented fuel elements), six control rods (5 fuel follower control rods and 1 air follower control rod), 18 graphite elements, one dry central thimble, one pneumatic transfer system irradiation terminus, and one neutron source [6,16]. All of these elements are placed and supported in-between two 55.25 cm diameter grid plates and arranged in a hexagonal lattice. The reactor is controlled by six control rods, which contain boron carbide (B_4C) as the neutron absorber material. Fig. 1 shows the reactor tank with concrete structure, and Fig. 2 shows the reactor cooling systems. The reactor is housed in a hall of 23.5 m × 20.12 m having a height of 17.4 m. The volume of the reactor hall is 8202.65 m^3 [4]. The reactor cooling system is designed to maintain the flow of demineralized water through the reactor core at a rate of 13230 L/min so as to remove the 3 MW thermal power being produced in the core from thermal fission. The coolant enters the reactor tank through a 25.4 cm line which penetrates the side of the tank near the top of the pool. The coolant is drawn by pump suction through the core upper shroud, down through the reactor core, and into the core lower plenum. From the lower plenum, the coolant enters a 30.5 cm diameter pipe and travels in a shielded trench to the gamma-emitting N-16 decay tank and then to the suction side of the primary pumps. Two pumps operating in parallel circulate the coolant through the heat exchanger and back to the reactor tank.

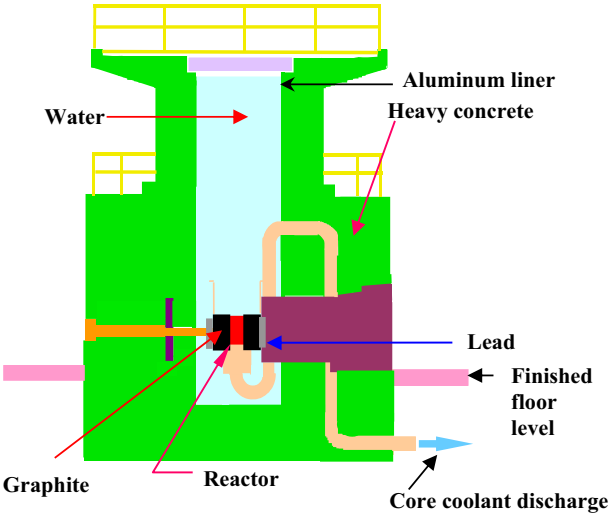

Fig. 1. Reactor tank with concrete structure.

3. Method of N-16 generation

Oxygen was discovered independently by Carl Wilhelm Scheele, in Uppsala, in 1773 or earlier, and Joseph Priestly in Wiltshire, in 1774, but Priestly is often given priority [Parks et al. [11]]. Naturally occurring oxygen is composed of three stable isotopes ^{16}O, ^{17}O and ^{18}O, with ^{16}O being the most abundant (99.72% natural abundance) ["Oxygen Nuclides/Isotopes", [10]]. The solubility of oxygen in water is temperature-dependent ["Air solubility in Water", [1]]. During reactor operation, the water coolant flows through the reactor core and is exposed to an intense neutron flux [9]. Oxygen-16 present in the reactor core water that interacts with fast neutron and gets converted into highly radioactive N-16 according to the following (n, p) reaction:

$$n + {}^{16}O = {}^{16}N + p + \gamma \quad (1)$$

The radioactive product decays with a half-life of 7.14 s, and approximately 75% of the decay emits a 6.13 MeV gamma ray. For conservatism, it is assumed that all decays emit a 6.13 MeV gamma ray. The primary water containing this highly radioactive N-16 is passed through the N-16 decay tank (capacity: 32,000 L), which holds the water for 143 s before it enters into the primary pumps [4]. During this period, activity of the short-lived N-16 ($T_{1/2} = 7.14$ s) decays down to low level.

4. Calculation methodology for N-16

4.1. N-16 activity concentration estimation under NCCM

The following calculations are performed to evaluate the activity concentration for N-16 in the region of reactor core, reactor tank, and reactor bay at different reactor power levels during NCCM. The concentration of N-16 atoms per cm^3 of water as it leaves the reactor core is given by [8]

$$N^N = \frac{\varphi_v N^o \sigma^o}{\lambda^N}\left[1 - e^{-t_c \lambda^N}\right] \quad (2)$$

where, N^N= N-16 atoms per cm^3 of water.

The thermal power produced by a reactor is directly related to the volumetric flow rate of the reactor coolant and the temperature rise across the reactor core. For reactor operation at 500 kW, the volumetric flow rate of the water through the core is given by [Ajijul et al [3]],

$$v_1 = \frac{P}{\delta T \rho C_p} \quad (3)$$

$$v_1 = 1.97 \times 10^4 \mathrm{cm}^3 \big/ \mathrm{sec}$$

The average exposure time in the reactor is given by:

$$t_c = \frac{\rho V_c}{v_1} \quad (4)$$

thus, $t_c = 3.47$ s.

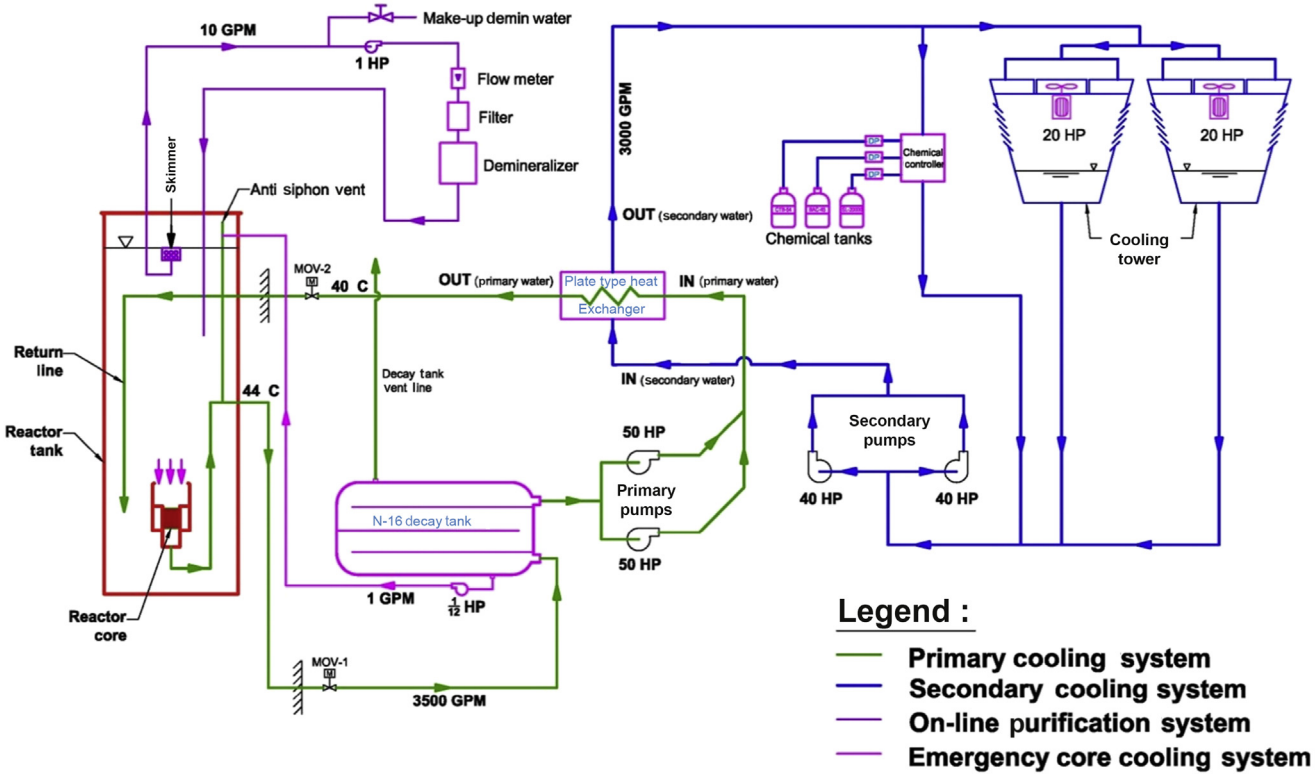

Fig. 2. Reactor cooling systems.

The activity added in the core water region is [8],

$$A_c = \varphi_v N^o \sigma^o \left[1 - e^{-t_c \lambda^N}\right] = 7.40 \times 10^5 \mathrm{Bq}/\mathrm{cm}^3 \quad (5)$$

Solving for N^N from Eq. (2) we obtain 7.65×10^6 atoms per cm^3 of water leaving the core.

Now, the N-16 activity concentration in the volume immediately above the tank water region is

$$A_t = \frac{7.65 \times 10^6 \times 9.70 \times 10^{-2}}{2.52 \times 10^7} = 2.94 \times 10^{-2} \mathrm{Bq}/\mathrm{cm}^3 \quad (6)$$

With a flow rate of 1.97×10^4 cm^3/sec, the rate of Nitrogen leaving the core is therefore 1.50×10^{11} atoms per sec.

An estimate of the fraction of nitrogen atoms in the tank water that escape each second can be obtained by examining the motility of ions in dilute solution. Most ions have velocities of the order of $3–8 \times 10^{-4}$ cm/sec under a potential gradient of 1 V per cm.

In the potential gradient, the nitrogen's velocity should be less than 3×10^{-4} cm/sec. Therefore, only the nitrogen atoms within 3×10^{-4}cm of the pool surface will be in a region in which the nitrogen atoms can leave the water within any given second. Actually, even this source volume is still too large. Nevertheless, it gives an upper limit for the fraction of the total Nitrogen atoms that can leave the water per second [Ajijul et al [3]]:

$$f^N_{2\to 3} \le \frac{1}{2} \frac{3 \times 10^{-4}\ \mathrm{cm/sec}}{\textit{water height}} = \frac{3 \times 10^{-4}\ \mathrm{cm/sec}}{822.96\ cm} = 1.82 \times 10^{-7}\ \mathrm{sec}^{-1}$$

Where it is assumed that one-half of the ions formed, namely the anions, remain in the water. Thus the number of N-16 atoms entering the reactor bay air is given by

$$f^N_{2\to 3} N^N_v = \frac{f^N_{2\to 3}(1.50 \times 10^{11})}{f^N_{2\to 3} + \lambda^N} = 2.81 \times 10^5 \frac{\mathrm{atoms}}{\mathrm{sec}}$$

where, subscript 1 = reactor core water region, subscript 2 = reactor tank water region (external to the reactor core), subscript 3 = reactor bay region. $f^N_{2\to 3}$ = fraction of N-16 atoms in reactor tank region that escape to the bay region per unit time, sec^{-1}.

In the reactor bay region, the activity is affected by dilution, ventilation, and decay. Therefore, the rate of accumulation of N-16 in the reactor bay as a whole is given by [USGS [SAR [14]]]

$$\frac{d\left(V_3 N_3^{16}\right)}{dt} = S - \left(\lambda^N + \frac{q}{V_3}\right) N_3^{16} V_3 \quad (7)$$

where, S = number of N-16 atoms entering the reactor bay from the reactor tank per second = 2.81×10^5 atoms/sec.

For saturation condition,

$$V_3 N_3^{16} = \frac{S}{\lambda^N + q/V_3} = 2.87 \times 10^6 \mathrm{nuclei} \quad (8)$$

Eq. (8) corresponds to an activity concentration of the reactor bay region.

$$A_b = \frac{9.70 \times 10^{-2} \times 2.87 \times 10^6}{8.20 \times 10^9} = 3.39 \times 10^{-5} \mathrm{Bq}/\mathrm{cm}^3$$

The activity concentrations for N-16 at different reactor power levels during NCCM are estimated and are shown in Table 1.

Figs. 3–5 show the N-16 activity concentration with different reactor power levels in the region of reactor core, reactor tank, and

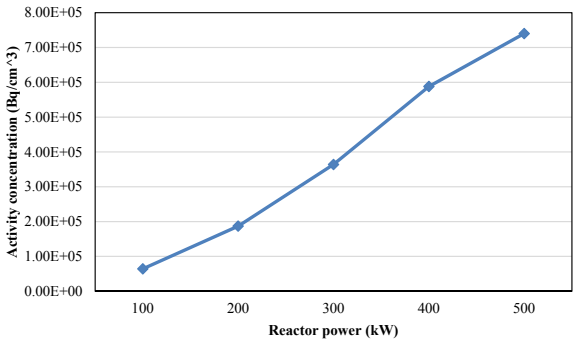

Fig. 3. N-16 activity concentration variations with reactor power in the core region.

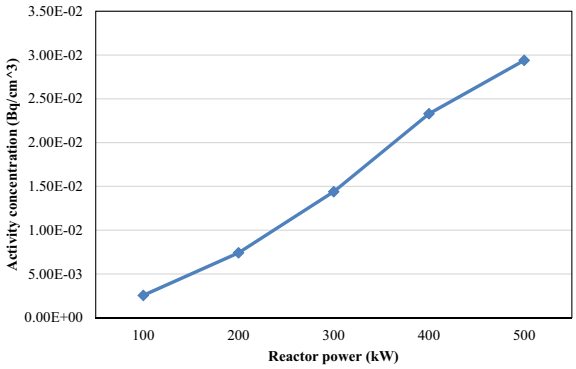

Fig. 4. N-16 activity concentration variations with reactor power in the tank region.

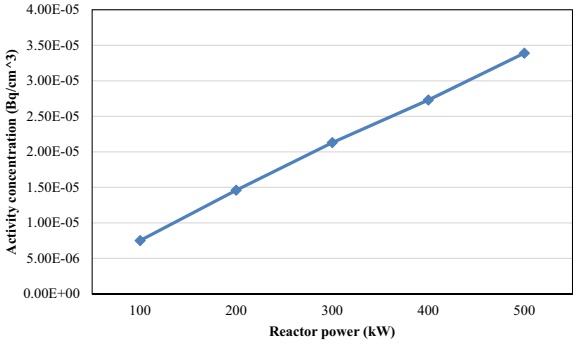

Fig. 5. N-16 activity concentration variations with reactor power in the bay region.

reactor bay with NCCM. It is shown in Fig. 3 that under 100 kW reactor power, the obtained N-16 activity concentration value in reactor core region is 6.43×10^4 Bq/cm^3 which was increased to 7.40×10^5 Bq/cm^3 for 500 kW reactor power. For reactor tank region under 100 kW reactor power, the obtained N-16 activity concentration value was 2.56×10^{-3} Bq/cm^3, and at 500 kW reactor power, the obtained N-16 activity concentration value was 2.94×10^{-2} Bq/cm^3 which is shown in Fig. 4. Fig. 5 shows the obtained N-16 activity concentration value which was 7.51×10^{-6} Bq/cm^3 for reactor bay region at 100 kW reactor power$\times 10^{-6}$ Bq/cm^3, and at 500 kW reactor power, the obtained N-16 activity concentration value is 3.39×10^{-5} Bq/cm^3. It is found from these figures that the N-16 activity concentration sharply increases with the increase of reactor power. The obtained N-16 activity concentration value in the reactor core region is dominant when compared with other two regions.

4.2. N-16 activity concentration estimation in the decay tank exit water under FCCM

The $^{16}O(n, p)^{16}N$ reaction produces the majority of radioactivity in the coolant during reactor operation. High-energy gamma rays accompany the decay of N-16 [17]. The production rate for N-16 in the reactor core at 3000 kW is [13],

$$\sum \varphi_v = N\,{}^{o}\sigma\,{}^{o}\varphi_v = 1.55 \times 10^7 \frac{\text{nuclei}}{\text{cm}^3} - \text{sec} \tag{9}$$

where, $\sum$ = macroscopic cross section.

During reactor operation at 3 MW with FCCM, the primary water flow rate across the core is 13230 L/min [4]. Table 1.

Thus the volumetric flow rate of the water through the reactor core is,

$$v_1 = 2.20 \times 10^5 \text{ cm}^3/\text{sec}$$

Using Eq. (4), the average exposure time in the reactor can be given by:

$$t_c = \frac{0.958 \times 7.15 \times 10^4}{2.20 \times 10^5} = 0.31 \text{ sec}$$

As the water passes through the core, the rate at which the concentration of a radioactive isotope in the water changes is [8], (Table 2)

$$\frac{dN}{dt} = \sum \varphi_v - \lambda^N N \tag{10}$$

Therefore, the activity added in the core exit water is [8]

$$A_c = \lambda^N N = \sum \varphi_v \left[1 - e^{-t_c \lambda^N}\right] = 4.46 \times 10^5 \frac{\text{Bq}}{\text{cm}^3} \tag{11}$$

The transit time through the decay tank is given by:

$$t_d = \frac{\rho V_d}{w} \tag{12}$$

thus, $t_d = 143.18$ s.

The N-16 activity concentration in the water exiting decay tank is [8], (Table 3)

Table 1
Numerical values of different parameters with symbol and their meanings.

Symbol and meaning	Value
λ^N, decay constant for N-16, (sec^{-1})	9.70×10^{-2}
σ^O, absorption cross-section of oxygen (cm^2) [7]	2.13×10^{-29}
φ_v, core average fission neutron flux at 500 kW, (n/cm^2-sec)	3.65×10^{12}
v_1, volume flow rate of the water through the core at 500 kW, (cm^3/sec)	1.97×10^4
P, reactor power, (watts)	5×10^5
C_p, specific heat of the water, (watt.sec/g. $^\circ$C)	4.19
δT, temperature rise across the core, ($^\circ$C)	6.3
ρ, exit water density, (g/cm^3)	0.958
V_c, core water volume exposed to flux φ_v, (cm^3)	7.15×10^4
V_2, volume of reactor tank water region external to the reactor, (cm^3)	2.52×10^7
V_3, volume of reactor bay region, (cm^3)	8.20×10^9
t_c, average time of exposure in reactor, (sec)	3.47
N^O, oxygen atoms per cm^3 of water	3.34×10^{22}
q, volume flow rate from reactor bay exhaust, (cm^3/sec)	4.72×10^6

Table 2
Data for N-16 activity concentration estimation at different reactor power levels with NCCM.

Reactor power (kW)	Temperature difference (°C)	Average exposure time (sec)	Neutron flux (n/cm^2-sec)	N-16 activity concentration (Bq/cm^3)		
				Core region	Tank region	Bay region
100	0.5	1.37	7.30×10^{11}	6.43×10^{4}	2.56×10^{-3}	7.51×10^{-6}
200	1.5	2.06	1.46×10^{12}	1.87×10^{5}	7.42×10^{-3}	1.46×10^{-5}
300	3	2.75	2.19×10^{12}	3.64×10^{5}	1.44×10^{-2}	2.13×10^{-5}
400	5	3.44	2.92×10^{12}	5.88×10^{5}	2.33×10^{-2}	2.73×10^{-5}
500	6.3	3.47	3.65×10^{12}	7.40×10^{5}	2.94×10^{-2}	3.39×10^{-5}

NCCM, natural convection cooling mode.

Table 3
Numerical values of different parameters with symbol and their meanings.

Symbol and meaning	Value
φ_v, core average fission neutron flux at 3000 kW, (n/cm^2-sec)	3.65×10^{12}
v_1, volume flow rate of the water through the core at 3000 kW, (cm^3/sec)	2.20×10^{5}
P, reactor power, (watts)	3×10^{6}
$V_{d,}$ volume of decay tank water region, (cm^3)	3.15×10^{7}
t_c, average time of exposure in reactor at 3000 kW, (sec)	0.31
w, decay tank volumetric flow rate, (cm^3/sec)	2.20×10^{5}
t_d, transit time through the decay tank, (sec)	143.18

$$A_d = A_C e^{-t_d \lambda^N} = 4.14 \times 10^{-1} \frac{Bq}{cm^3} \quad (13)$$

This value of N-16 activity concentration is very much lower than the activity concentration in the reactor core region. Thus the activity added in the decay tank exit water is not harmful for human health or the environment.

5. Conclusions

During reactor operation the activity in cooling water can be induced by short-lived radionuclide N-16 through fast neutron reactions with O-16 atoms present in primary water. In this study, we focused on the activity concentration estimation of this short-lived gamma emitter N-16. During reactor operation with NCCM, the N-16 activity concentration distribution in the reactor core, tank, and in the bay region at different reactor power levels is determined. Results show that the activity concentration value for N-16 within the reactor bay region at 500 kW reactor power is 3.39×10^{-5} Bq/cm^3, which is not hazardous. Thus the assessment performed within this article ensures that during reactor operation release of N-16 activity to the reactor bay region do not present any significant radiological hazard to the reactor staff although the N-16 activity within the core region is dominant. It is also found from the estimated N-16 activity concentration during high-power operation with FCCM that the activity in the water exiting decay tank is negligible compared with the reactor core region. Therefore, it is ensured that during normal reactor operation condition there is no possibility to release any major N-16 activity from the reactor facility which can make any significant impact on occupational worker as well as to general public or the environment. The obtained results from the present study is significant for determining the dose constant at working areas and can also be utilized as baseline data for the research reactor.

Conflicts of interest

The authors declared that there are no conflicts of interest.

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