Tritium Production from Nitrogen in a Tokomak Reactor Resulting from a Neutron Source

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ABSTRACT
Tritium is an important isotope of hydrogen used in deuterium-tritium (D-T) fuel in nuclear fusion reactors, but it is only naturally occurring on Earth in the upper atmosphere resulting from galactic cosmic radiation (GCR) interactions, which produces small amounts of tritium. This poses a problem because tritium is an important component for nuclear fusion reactors that utilize deuterium-tritium (D-T) fuel. This study investigates tritium production by applying the nuclear reaction resulting from GCR interactions and a mathematical model for the flux of neutrons that reflect the energy levels associated with the resulting neutrons from D-T reactions to a two-dimensional domain representing the tritium production layer in a tokomak reactor. The results of this study indicate that for a feasible amount of tritium production, the nitrogen density must be exceptionally higher than that of nitrogen gas. As such, GCR interactions do not produce a feasible source of tritium production for D-T fuel.

KEYWORDS
Galactic Cosmic Rays; Tokamak; Tritium; Neutron; Neutron Diffusion; Nuclear Fission; Tritium Breeding Ratio; Tritium Production

INTRODUCTION

Tritium is a radioactive isotope of hydrogen that is rare on Earth with few natural sources, including galactic cosmic ray (GCR) interactions in the upper atmosphere.[1] GCRs are composed of highly accelerated light particles, mostly protons and neutrons, that collide with particles in the upper atmosphere.[2] Interactions of this nature cause the formation of tritium by a neutron, from the GCR, colliding with a nitrogen atom, and can be shown by the reaction equation,

$$ {}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{12}_{6}C + {}^{3}_{1}H \,, \qquad \textbf{Equation 1.}$$

where ${}^{14}_{7}N$ is nitrogen, ${}^{1}_{0}n$ is the neutron from the GCR, ${}^{12}_{6}C$ is carbon, and ${}^{3}_{1}H$ is the tritium.[1] In addition to the natural fission reaction described by this equation, tritium is also produced artificially in nuclear reactors because of its usefulness in tokomak fusion reactors.

Tokomak fusion reactors are toroidal shaped nuclear reactors designed to confine plasma using magnetic fields. The plasma for these reactors can consist of deuterium-deuterium (D-D) fuel or deuterium-tritium (D-T) fuel. Deuterium is a non-radioactive isotope of hydrogen that is present in large concentrations in sea water.[3] While deuterium is more abundant on Earth than tritium, the energy production associated with D-D fuel is only 3.27 MeV whereas it's 17.7 MeV for D-T fuel.[3] Additionally, the reaction cross section of D-T fusion is markedly higher at lower temperatures as compared to D-D fusion.[4] Therefore, artificially producing tritium is an important consideration for tokomak reactors.

To accomplish tritium production in tokomak reactors, a lithium plasma-facing component is typically incorporated into the reactor which acts as a source to artificially produce tritium. This is termed a breeding blanket and has been shown to significantly improve the reactors performance.[5] Lithium is an extremely reactive metal with a relatively low melting temperature, and the breeding blanket layer is designed to evaporate and ionize, allowing neutrons to regularly collide into the lithium ions.[5] This collision produces a fission reaction resulting in a byproduct of tritium.

The work contained herein investigates applying the reaction in **Equation 1** to a 2D, rectangular domain (see **Figure 1**) simulating a breeding zone of a tokomak reactor. A literature review reveals this application of atmospheric tritium production as a breeding method for fusion reactors as original, although the use of GCRs to create nuclear fuel for lunar fission reactors has been previously considered.[6] The domain herein is simplified to be a medium consisting solely of nitrogen atoms, and is subjected to an incoming neutron source that reflects the energy levels of the neutrons from D-T fuel reactions. These neutrons move into the domain and collide with the nitrogen to form tritium. This paper describes the theoretical construction of the model, application to the domain, and resulting amount of tritium produced.

THEOERTICAL BACKGROUND

The kinetic theory of gases describes the movement of particles and can be used to build a model for the movement of neutrons. When applied to the domain of a simplified breeding zone of a tokomak reactor, tritium produced resulting from neutron collisions can be investigated. This motion is governed by the Boltzmann transport equation and can be written as,

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V N\mathrm{d}^3\boldsymbol{r} = \int_V S\mathrm{d}^3\boldsymbol{r} - \int_V N\boldsymbol{v}\Sigma_c\mathrm{d}^3\boldsymbol{r} - \oint \boldsymbol{J}\cdot\boldsymbol{n}\mathrm{d}A, \qquad \textbf{Equation 2.}$$

where N describes the velocity distribution function, V is the volume for which the equation is applicable, $\boldsymbol{r}$ is the position vector, S is the source being added, $\boldsymbol{v}$ is the velocity, Σ_c is the macroscopic reaction cross section of radiation capture (which allows one to determine the likelihood a reaction will occur), $\boldsymbol{J}$ is the source being lost, and t is time.[7] This equation represents the general motion of a particle due to any external sources, intermolecular interactions, and advection. It can be simplified by imposing a diffusion approximation based on Fick's Laws of Diffusion forcing the neutrons to transport solely via diffusion.

This is accomplished by imposing that there are no strong point sources of neutrons within the medium which the neutrons interact, resulting in a uniform distribution of nitrogen. With this uniform distribution, Σ_c becomes independent of the position of the neutron in the domain.[7] Furthermore, for the purposes of this analysis, neutron collisions are assumed to occur isotropically and particle scattering is assumed to be elastic. This implies that the resulting neutron has the same energy as the incoming neutron.[8] Additionally, focusing on the steady state dynamics of a cross-section of the breeding blanket without any flux discontinuities, **Equation 2** can be simplified to the following in a Cartesian coordinate system,

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} - \frac{\Sigma_c}{D}\phi = \frac{-S}{D}, \qquad \textbf{Equation 3.}$$

where ϕ is the neutron flux, S is a neutron source, and D is the diffusion coefficient defined as,

$$D = \frac{\Sigma_s}{3\Sigma_t^2}, \qquad \textbf{Equation 4.}$$

where Σ_s is the elastic scattering macroscopic interaction cross section, and Σ_t is the total macroscopic interaction cross section.[7]

Solving **Equation 3** for the neutron flux allows the tritium breeding ratio (TBR) to be calculated. The TBR is used in nuclear fusion reactor analysis to ensure there is enough tritium being produced to sustain the system. It can describe the amount of tritium produced over the amount of tritium fused, and can be written as,[9]

$$TBR = \frac{\int \Sigma_c\phi\mathrm{d}V}{\int S\mathrm{d}V}. \qquad \textbf{Equation 5.}$$

When ϕ as a function of location in the domain is determined via **Equation 3**, the TBR can be calculated to determine if the tritium production method from a given neutron source is feasible. The macroscopic cross sections used in this analysis (Σ_c, Σ_s, and Σ_t) are calculated from the microscopic cross sections,

$$\Sigma = \sigma N, \qquad \textbf{Equation 6.}$$

where Σ is the macroscopic cross section, σ is the microscopic cross section, and N is the atomic number density, defined as,

$$N = \frac{\rho_N N_A}{M}, \qquad \textbf{Equation 7.}$$

where ρ_N is the nitrogen density, N_A is Avogadro's number, and M is the molar mass of nitrogen.[10]

MODEL APPLICATION

The neutron flux into a medium of nitrogen resulting in the neutron-nitrogen reactions described in **Equation 3** is applied to the domain depicted in **Figure 1**. To maintain independence on the physical size of the domain, Neumann conditions were applied to the domain's boundary. However, to simulate neutrons interacting with the breeding blanket modelled by this domain, one portion of a boundary had a Dirichlet condition imposed representing an inlet of neutrons entering the system. Since steady state dynamics are of interest, this condition represents a constant neutron source. To completely define the domain, w, l, and a were chosen to be 0.5 cm, 0.5 cm, and 0.0526 cm respectively.

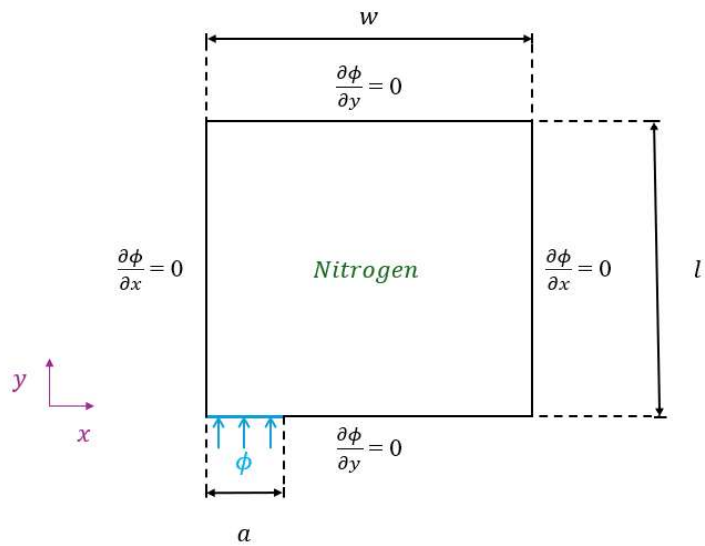


Figure 1. A schematic of the domain representing the breeding blanket. The bottom left corner of the domain has a constant flux source representing neutrons entering the domain whereas the other boundaries only define the derivatives of the flux allowing any value of flux to exist, effectively making the physical domain size *w* by *l* irrelevant.

It should be noted that the source terms in **Equations 3** and **5** need not be the same. Specifically, S in **Equation 3** may be defined as a description of the system with respect to the neutron multiplication factor. This multiplication factor describes the ratio of the number of neutrons over time adjacent generations.[11] This can take one of three different cases, subcritical, critical, or supercritical. Here, the neutron multiplication factor was taken to be subcritical because the amount of neutrons in the system is decreasing as the reactions described by **Equation 1** occur. Additionally, by focusing on steady state dynamics, generational dependency can be neglected, and therefore the multiplication factor can be considered constant.[11] This source definition accounts for the probability of a neutron to be captured in the domain because Σ_c is included, and can be written as,

$$S = \Sigma_c k_{\text{mult}} \phi \, , \qquad \textbf{Equation 8.}$$

where k_{mult} is the neutron source multiplication factor.[7] Since the multiplication factor was taken to be subcritical and the containment material is taken to be C45, the neutron source multiplication factor is taken to be $k_{\text{mult}} = 0.99273$.[11]

The source in **Equation 5** represents the fusion neutron source i.e., the neutrons produced from fusion reactions. As the mathematical model does not have a formal fusion neutron source, the Dirichlet boundary condition can be considered as this source. In other words, the constant inlet of ϕ for a length of a at $y = 0$ is treated as the inlet from a fusion reactor source, similar to lithium breeding blankets being a plasma-facing component in a tokomak reactor. However, it should be noted that by defining the S of **Equation 5** in this way, the ratio is no longer a breeding ratio as this analysis does not consider the tritium that is fused because there are no fusion reactions in the domain of analysis. This new ratio can be described as a tritium production ratio (TPR), quantifying the amount of tritium produced per neutrons entering the system.

The boundary conditions depicted in **Figure 1** may be written as,

$$\left.\begin{matrix}\phi_x(0,y) = 0\\ \phi_x(w,y) = 0\end{matrix}\right\} \quad \text{for} \quad 0 < y < l, \qquad \textbf{Equation 9a.}$$

$$\phi_y(x,l) = 0 \quad \text{for} \quad 0 < x < w, \qquad \textbf{Equation 9b.}$$

$$\begin{matrix}\phi(x,0) = 0\\ \phi_y(x,0) = 0\end{matrix} \quad \text{for} \quad \begin{matrix}0 < x < a\\ a < x < w.\end{matrix} \qquad \textbf{Equation 9c.}$$

Imposing these on **Equation 3** results in a solution for ϕ over the domain. Due to the elliptic behavior of **Equation 3**, an analytical solution can be obtained using the method of separation of variables (an example of which can be found in **Section 9.4** of **Reference 12**) resulting in,[13]

$$\phi(x,y) = \sum_{p=0}^{\infty} C_p \cos\left(\frac{p\pi}{w}x\right)\cos\left(\sqrt{\frac{\Sigma_c}{D}(k_{\text{mult}}-1)-\left(\frac{p\pi}{w}\right)^2}\,y\right), \quad \text{Equation 10.}$$

where C_p is defined at $y = 0$ as,

$$C_p = \begin{cases} nv_n & \text{when } 0 \le x \le a \\ 1 & \text{when } a < x \le w \end{cases},$$

and n is the neutron density, and v_n is the neutron velocity defined as,

$$v_n = \sqrt{\frac{8kT}{\pi m}}, \quad \text{Equation 11.}$$

where k is Boltzmann's constant, T is temperature, and m is the mass of a neutron. It should be emphasized that the complete derivation of **Equation 10** can be found in **Reference 13**.

To determine the TPR on the solution domain, the volume integrals in **Equation 5** become area integrals. Furthermore, the area integral in the numerator can be written as a Reimann's summation over the domain and the dominator becomes a simple line integral because of the application of the constant source input. This transforms **Equation 5** into,

$$TPR = \frac{\sum_{i=1}^{w}\sum_{j=1}^{l}\Sigma_c\phi(x_i,y_j)}{anv_n}. \quad \text{Equation 12.}$$

RESULTS AND DISCUSSION

To analyze the effect of model parameters on the TPR, a range of neutron densities, nitrogen densities, and temperatures, are imposed upon the system and listed in **Table 1**. The range of neutron densities is based around values of a single impulse from a portable neutron generator which releases 1.5×10^8 neutrons/s at an energy level of 14 MeV,[14] the nitrogen densities cover a range of possibilities for nitrogen gas, and the temperatures correspond to the average temperature of lithium as a plasma facing component of tritium breeding blankets.[4]

T [K]	ρ_N [g/m³]	n [neutrons]
400	0.1	1.00E+07
450	1.251	1.25E+08
500	50	1.00E+09
550	100	5.00E+09
600	200	1.00E+10
700	300	1.50E+10
800	400	2.00E+10
900	500	4.00E+10
1000	1000	5.00E+10

Table 1. The range of values for the neutron density (n), nitrogen density (ρ_N), and the temperature (T) used in this study. It should be noted that these values are independent of each other.

The remaining parameters needed to completely define **Equation 10** are σ_c, M, N_A, m, and k. For an energy level of 14.1 MeV, similar to that of the portable neutron generator, the National Nuclear Data Center records that $\sigma_c = 1.679535 \times 10^{-5}$ barns, $\sigma_s = 9.6973995 \times 10^{-1}$ barns, $\sigma_t = 1.5706345$ barns for ${}^{14}_{7}N$.[15] The solution behavior of **Equation 10** for all cases in **Table 1** exhibit identical trends with differing magnitudes. A small region of high neutron flux due to the boundary condition of **Equation 9c** is clearly visible and rapidly diffuses into the remainder of the domain, seen in **Figure 2**.[13] This is a direct result of only containing transport via diffusion. Furthermore, the neutrons react with the immediately available nitrogen atoms as they move into the domain, so the neutrons are used immediately upon their entry into the system. In other words, the neutrons cannot travel a great distance into the domain because they are being used in reactions with the closest available nitrogen atoms, this in conjunction with the limited transport methods narrows their movement to the immediate vicinity of entrance into the domain.

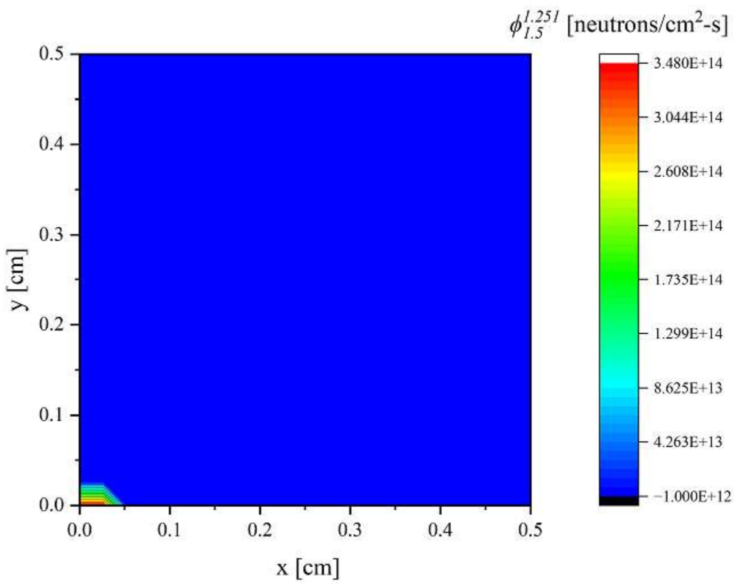
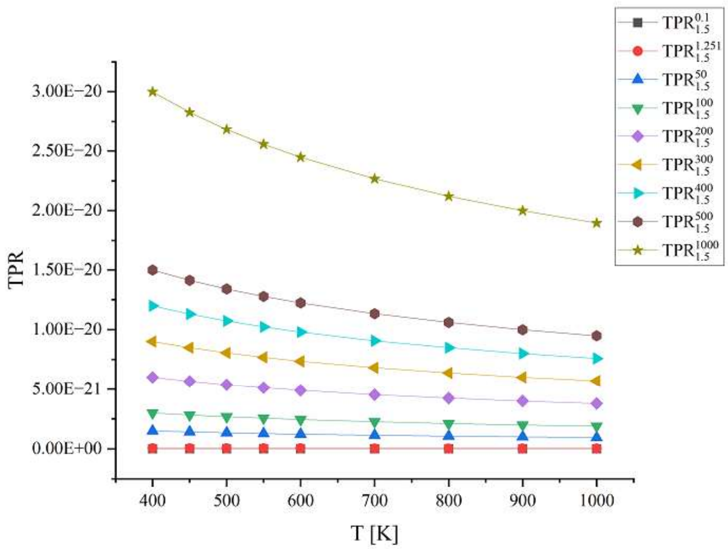


Figure 2. Distribution of the neutron flux in the computational domain for the first temperature case in **Table 1**. The superscript on ϕ indicates the nitrogen density and the subscript represents the neutron density resulting in this specific contour. Additional flux graphs for the other cases outlined in **Table 1** can be found in **Reference 13**.

With ϕ now established over the entire domain, the feasibility of tritium production can be investigated. It's desirable to have $TPR > 1$ which would mean the tritium produced matches the neutrons entering the system. The TPR was determined with **Equation 12** and there was an investigation into the effects of changing nitrogen and neutron densities over a range of temperatures. The nitrogen density has a more significant effect on the TPR values than the neutron density because diffusion only moves the neutrons in a restricted space for all neutron flux cases. Since the overall flux is not significantly impacted by changes in neutron density, the TPR values are not significantly affected either. This can be seen by the TPR values for the varying nitrogen density, as these results are consistently at an order closer to the target TPR than when the neutron density is varied as shown in **Figure 3**.[13] Additionally, the constant neutron density case exhibited results with the same order of magnitude for all nitrogen density cases, whereas at a constant nitrogen density, the results were on different orders of magnitude for the lower and upper neutron density cases.[13] This contrasts from the nitrogen density because as the nitrogen density increases, there are more nitrogen atoms within the space the neutron flux is the highest so there are more opportunities for neutron-nitrogen interactions over the entire computational domain. Furthermore, the neutrons cannot travel far into the domain, due to the limiting factor of diffusion transport. If the neutrons are restricted to the corner of the domain in which they enter, the number of neutrons becomes irrelevant because there is a finite number of nitrogen atoms available in a given space. Therefore, the nitrogen density has a more significant influence on the TPR values than the neutron density does.

The neutron flux nominally permeating into the domain shown in **Figure 2** and subsequent diminished effect of the neutron density as seen in **Figure 3** results from limitations of the current model. In particular, the diffusion approximation imposed on **Equation 2** assumes negligible advection which minimizes the distribution of appreciable neutron flux. Even if neutron transport was governed solely by Fick's Laws of Diffusion as indicated in **Equation 3**, the simplified 2D Cartesian domain itself may mitigate neutron motion. Consider the toroidal shape of a tokomak in comparison to the 2D square shown in **Figure 1**, for example. The toroid would have a much larger surface area at which flux enters the domain as opposed to the line that it enters the 2D square domain. Of course, if neutrons travel further into the computational domain, then the neutron density would have a more appreciable effect than that shown in **Figure 3**. Three-dimensional dynamics incorporating advection would result in a remarkably more complex analytical solution than that found in **Equation 10**, especially if transient dynamics were additionally considered. These model modifications may be best dealt with using a Monte Carlo-type simulation as compared to a deterministic solution highlighted herein. One possibility would be the Monte Carlo N-Particle code developed by Los Alamos National Laboratory.[16] The inclusion of these more realistic constraints is considered a topic for future study.

a)



b)

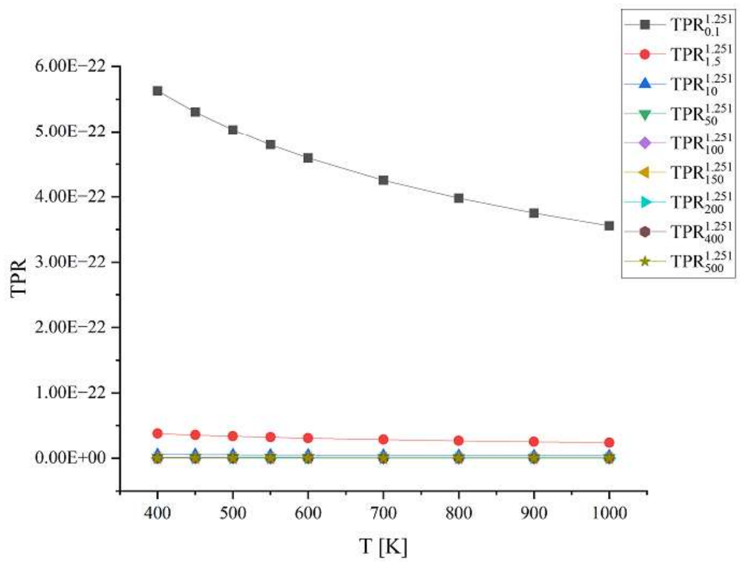


Figure 3. The effects of nitrogen density (a) and neutron density (b) on the TPR. The superscript in the legend indicates nitrogen density and the subscript represents the neutron density for the particular plotted ase. The magnitude of the TPR when changing the nitrogen density indicates that the nitrogen density has more significant effect on the TPR as compared to the neutron density.

Using a baseline of $n = 1.5 \times 10^8$ neutrons and including the multiplication factor of $10^{11.07}$, a contour of the TPR as a function of ρ_N and temperature is depicted in **Figure 4.** As expected, when ρ_N increases, the TPR also increases because there are more nitrogen atoms in the system creating more cross sections i.e., more possibilities for interactions. Additionally, as temperature decreases, TPR increases due to the decrease in microscopic cross-sections for neutrons as energy increases.[15] The increase in kinetic energy would generate more movement on the molecular level, but the neutron cross sections are smaller. This makes the interactions less likely at higher temperatures because the neutron needs to collide with a smaller target to obtain a desired interaction, in this case tritium production. For the current system, to have an appreciable TPR, $\rho_N > 7.5 \times 10^7$ g/cm^3 which is significantly higher than the density of nitrogen gas, again stressing that a single portable neutron source is not a feasible method of producing tritium.

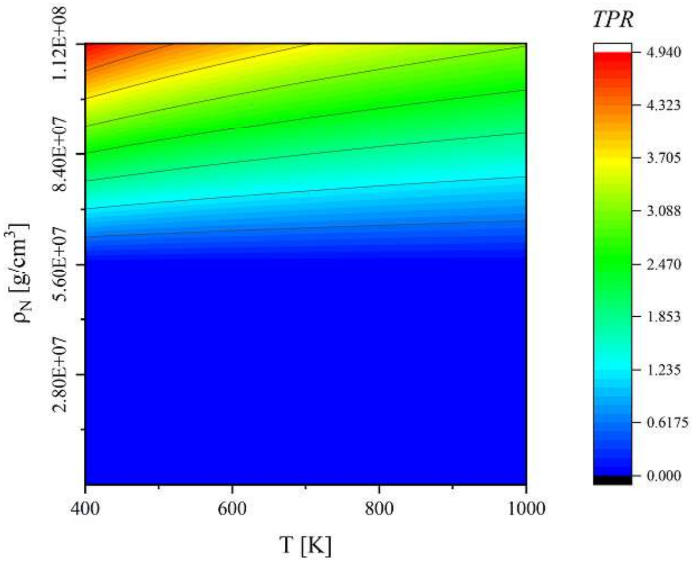


Figure 4. A contour representing the TPR results for a fixed neutron density over the range of temperatures considered in **Table 1**. Tritium production is considered feasible when the value of the TPR is greater than 1.

The TPR resulting from a portable neutron generator produces in an insufficient amount of tritium to be considered a viable source. To obtain feasible values of the TPR, the strength of the neutron generator needs to increase considerably. When a multiplication factor of $10^{11.07}$ is incorporated into **Equation 12**, desirable TPR values are met. It should be emphasized that while this is a large multiplication factor, it simply means the portable neutron generator imposed through **Equation 9c**, will not create a useful amount of tritium on its own for the specified domain and model limitations. This could be altered by incorporating a more realistic 3D domain and particle transport dynamics such as advection. Using that more complex, realistic model, the feasibility of using GCRs for nuclear power in extraterrestrial applications akin to **Reference 6** could be investigated.

CONCLUSION

This study explores applying tritium production reactions from galactic cosmic radiation by imposing an interaction with a portable neutron source and a tritium breeding blanket in D-T fueled tokomak fusion reactors. The neutron flux in a simplified 2D domain was analytically solved for and it was found that the flux does not deeply diffuse into the domain. The tritium production ratio due to this flux was calculated which showed a more significant dependency on the nitrogen density as compared to the neutron density. For a baseline scenario to produce a feasible amount of tritium, the density of nitrogen would need to far exceed the density of nitrogen gas. As such, a portable neutron source is not a feasible method of producing tritium for use in tokomak fusion reactors. This analysis could be modified to incorporate other modes of transport in addition to diffusion, with the intention of promoting further neutron distribution into the system.

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PRESS SUMMARY

Tritium is an important isotope of hydrogen for the preferred fuel for nuclear fusion reactors, but it is rare on earth. It only occurs naturally in the upper atmosphere due to interactions of nitrogen in the atmosphere with high energy particles from space called galactic cosmic radiation. Because tritium is important for fusion reactors, there are methods to produce tritium inside of the reactor to allow energy production to continue during operation. This paper investigates tritium production with nitrogen to recreate the natural tritium production akin to galactic cosmic radiation reactions inside of a nuclear fusion reactor. The results of this study indicate that this method of tritium production is not sufficient for successful nuclear fusion reactor operation.