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Neutron monitoring becomes important from the view point of radiation protection due to the development of nuclear fusion as worldwide energy source. Neutrons are generated by D-D and D-T reactions in the nuclear fusion facilities with energies 2.45MeV and 14.1MeV, respectively.

An appropriate instrument is essential for monitoring the dose accurately of wide energy range of neutrons. Conventionally Roentgen Equivalent Man (REM) counters have been used to measure the neutron dose with energies from thermal to tens of MeV. However, it is recognized that the REM-counters include error for measuring the dose, especially in the intermediate energy range around 0.1keV to 100keV. Therefore an energy independent neutron dose monitor with multiple moderators and absorber has been studied, in order to improve the dose response compared to the existing instrument.

The dissertation contains three topics: (1) Design study of the spherical type neutron dose monitor (2)Evaluation of neutron dose with irradiation experiments using standard sources and (3)Estimation of resultant incident angle of two directional sources and the method of dose evaluation.

The monitor has been designed; (i) To obtain improved dose response over a wide energies of neutrons compared to existing instruments, especially in the range of intermediate energies of neutrons, and (ii) To get the uniform sensitivity to neutron that comes from any direction. It was designed using three depths of thermo-luminescent dosimeters (TLDs) with composition of $^{6}LiF:CaSO_4(Tm)$, in order to get the specific responses to low and intermediate energies of neutrons and fast neutrons. As the size of the TLDs is small, multiple ones can be placed at different depths. Twelve radial directional TLDs are arranged between the layers at two consecutive depths and one in the centre to get isotropic sensitivity to neutrons.

The monitor consists of four layers of spherical shells in the order of from outer to inner; poly-methyl methacrylate (PMMA), boron nitride (BN), polyethylene(PE) and core PE. After moderation by the PMMA, the thermal and low energy of neutrons are detected by the first depth TLDs. The intermediate energies of neutrons after moderation by PMMA, BN and PE are detected by the third depth TLDs. Finally the fast neutrons are detected by the core TLDs. Monte Carlo N-particle transport code, MCNP5 was used for the design of the monitor. Neutron cross-section libraries of Japanese Evaluated Nuclear Data Library, JENDL-3.3 were applied for the calculations. The calculation was performed to get the response of the TLDs with the reaction of 6Li(n, α) T. Based on the specific response to three energy groups of neutrons, the dose can be described by linear combination of TLDs responses. The linear co-factors were derived by adjustment between the expected dose of D2O-moderated 252Cf source with 52 energy bins ranging from 0.414eV to 15MeV and TLDs responses. The D_2O-moderated ^{252}Cf source was applied, because it is the standard source mentioned in ISO8529 and it has wide energy spectrum. The optimum thickness of the moderator was obtained; 30mm PMMA, 40mm BN, 10mm PE and 35mm core PE by varying the thickness of first two layers and comparing the square sum of dose ratios for two different neutron incident directions and the ideal line of unity. The ratio of calculated dose by using each energy bin of neutrons to expected dose varied from 0.7 to 1.5 in the energy range from 0.414eV to 5MeV. On the other hand the ratio of REM counters was found from 0.4 to larger than 5. The exposure dose from neutrons higher than 5MeV can be neglected because expected neutron fluence would be remarkably decreased.

A prototype monitor was constructed, in order to demonstrate the performance of the monitor by irradiation experiment. The calibration of the monitor was performed by D_2O-moderated ^{252}Cf source at the Facility of Radiation Standards, FRS, of Japan Atomic Energy Agency, JAEA. A linear relationship was obtained between the TLD readout data and MCNP calculated value and then using this relationship the dose equation was derived for evaluating the dose. Irradiation experiments were also per-formed using ^{252}Cf bare and ^{241}Am-Be sources, in order to compare the evaluated doses among the different energy spectrum of neutrons. The dose evaluated by different irradiation experiment was close to the irradiated dose within about 50% uncertainty. The angular resolution of the monitor was estimated as a solid angle of less than 60°. Although at the FRS the dose was evaluated for known irradiation distance, in the practical field the distance of the neutron source would be unknown. A relationship is needed between the fluence and the dose for unknown distance. In case of parallel beam the neutron fluence does not vary with distance for a certain limit, it can be used at unknown irradiation distance. The dose was also evaluated using the co-factors for parallel beam of neutrons. The obtained result was as good as the point source. It is concluded that the co-factors of parallel neutron beam can be applied for evaluating the dose at any irradiation distance. The lower limit detection of the monitor was estimated to be 0.2mSv which is smaller than the regulatory dose limit of 1.3mSv/3months at outside of the boundary of radiation controlled areas in Japan. The usefulness of the monitor was shown with applying to the neutron spectrum calculated assuming outside of the wallet a fusion reactor room.

In order to demonstrate the performance of the dose monitor for the neutrons ir-radiation with different incident angles, simulation was done by MCNP5. At first the monitor was irradiated using a single neutron source with incident angles from -90° to +90°at 30° interval, to get the different angular responses. A parallel neutron beam of 50 cm radius with uniform density was assumed to be injected. Also two different sources of D_2O- moderated ^{252}Cf and bare ^{252}Cf were used to get the responses of detectors. The incident direction of single neutron source can be estimated from distribution of the first depth 12 TLDs responses with less than 30 ° angular resolution.

The TLDs responses from two directional sources were obtained by summing the responses of two single sources with different angles. The direction of neutron source was estimated by comparing the first depth 12 TLDs response distribution of two sources with those of single source in every incident angle. The neutron dose was evaluated by linear combination using three depths of selected TLDs responses and linear co-factors. The ratio of calculated to expected dose was within the ranges from 0.94 to 1.08 which is close to the unity.

As conclusion, the developed multi-layer spherical type neutron dose monitor was found to be independent to the wide range of energy spectrum and to show almost isotropic directional sensitivity for any incident neutrons. The lower limit detection was estimated less than 0.2 mSv and dose measurement uncertainty was about 50%. That is sufficient to use as a dose monitor for radiation safety management not only in the fusion facility but also for other neutron producing fields.

博士論文審査結果の要旨

エネルギー源としての核融合炉実現に向けた研究の進展にともない、核融合反応に伴って発生する最大 14MeV の中性子に起因する放射線防護のための測定が重要になっている。核融合炉の遮蔽壁の外では、0.025eV の熱中性子から 14MeV の幅広い中性子エネルギースペクトルとなり、また多様な方向からの照射場になり得るため、これに対応できるコンパクトな中性子モニターが欠かせない。一般的に中性子線量計ではポリエチレン等を用いて熱中性子まで減速させ、物質との核反応で生じる荷電粒子を利用している。従来の可搬型中性子線量計 REM カウンターでは、検出器をポリエチレン等で囲むのみであるため、0.1-100keV 付近の中性子が最も熱中性子化され易く、入射エネルギーから予測される線量当量に対して線量計応答値は 5 倍程になる。また、線源を用いた測定では予測される線量評価値に対して 2.4 倍程高い値を示した。この欠点を改善するため、低、中、高エネルギーの 3 つの領域に対応するように厚さの異なる減速材を 3 層化して各層の間に小型検出素子を配置する多層多面型の線量計を考案し、前記の応答値 2 倍以下、線量評価値に対して約 1.5 倍とし、かつ線源の方向によらない線量計の実現を目指した。具体的には、第 1 層の減速材の後に中性子吸収材(窒化ボロン)層を設けた 4 層の球形構造とし，第 1 層の後、第 3 層の後に各 12 カ所および中心に熱中性子に感応する ^{6}Li を含む熱ルミネッセンス線量計 TLD 素子を等方的に配置する構成とした。このように各 TLD の位置において非等方的な中性子入射と幅広いエネルギーに対応できるように考え、各位置での応答特性を評価し、最適化を行った。ここで中性子の輸送計算はモンテカルロ計算コード MCNP5 により行い、核断面積データは JENDL ライブラリーを用いた。まず減速材と吸収材の最適な厚さを計算により評価し、30+40+10+35 mm とすると、大きな変動が予想された 0.41eV-5MeV のエネルギー領域における応答比は、REM カウンターが 0.4～5 倍であったのに対して 0.7～1.5 倍の範囲に収まることを示した。なお、5MeV 以上の領域では想定している中性子も減少するため、線量全体への寄与は無視できる。次に、実際に球形 4 層の線量計を製作し、日本原子力研究開発機構の放射線標準施設においてエネルギースペクトルが既知の重水減速 ^{252}Cf 中性子線源を用いて、この球形線量計へ照射を行った。照射後、TLD 素子を取り出し、各位置の TLD 読み取り値と予測される線量との間に直線性があることを確認し、TLD 読み取り値と中性子線量とを関係づける係数を求めた。この関係を用いることによって、異なるエネルギースペクトルを持つ線源に対しても線量評価を行い、計算と実験から線量評価誤差が約 50%という高い精度を確認し、検出限界は約 0.2mSv となることを示した。これによって放射線管理に必要な感度 3 ヶ月当たり 1.3mSv を達成できることが分かった。さらに、中性子入射が非等方である場合の有効性を調べるために、計算により単一の標準線源照射において入射角を 0° から 90° まで変えて各 TLD 位置での応答を求め、少なくとも 60 度の立体角の差を明確に区別できることを示した。また、入射角の種々異なる 2 個の標準線源を想定して各線源の強さを変えた計算を行ない、各 TLD の応答を比較評価した。その結果、各 2 層の強度の高い 3 個および中心の検出器の値を選ぶことにより、線源の入射方向に拘わらず十分な精度の線量測定が可能であることを示した。

以上、本研究は、線源の入射方向に依存せず、幅広い中性子エネルギースペクトルにおいても従来に無い約 50%という十分な精度を持つコンパクトな多面多層型の中性子線量計を初めて実現したものである。

以上から、本審査委員会は本申請論文を学位論文としてふさわしいものと認めた。