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Fast Neutron Generators: Radiation Levels and Shielding Requirements

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Fast Neutron Generators: Radiation Levels and Shielding Requirements

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Neutron and gamma radiation levels around a Cockcroft-Walton neutron generator producing 14-Mev neutrons at an approximate rate of 10^{10} neutrons per second were measured under conditions typical of those required for activation analysis. Neutron flux reduction to acceptable levels for limited operation was accomplished by 12 feet of distance that included shielding consisting of 27 inches of water and 16 inches of solid concrete block. Other radiation hazards encountered were the production of x-rays and the release of tritium from the target.

Introduction

THE use of neutron generators has become widespread because of their increased value for neutron activation analysis. The acceptance of neutron generators has taken place primarily because of their simplicity, relatively low cost, and high neutron output. One use of neutron generators is for the production of essentially monoenergetic 14-Mev neutrons by the reaction:

$$H^2 + H^3 \rightarrow n + He^4 + 17.577 \text{ Mev.}$$

This reaction takes place and has its maximum yield for thick targets at accelerating potentials below 150 kilovolts; the distribution of neutrons from the target is essentially isotropic. Neutron generators of the Cockcroft-Walton type, making use of the above reaction, are capable of producing neutron yields 1000 times greater than yields available from isotopic sources of neutrons, such as a one-curie plutonium-beryllium source. The neutron generator of this study is a Cockcroft-Walton type of accelerator, Model 150-1H, made by the Texas Nuclear Corporation. The acceleration potential may be varied from 0 to 150 kilovolts. The particles normally accelerated are ionized hydrogen or deuterium produced in a radio-frequency ion source of the Oak Ridge National Laboratories (ORNL) type. A full description of the unit may be found in the instrument manual provided by the company. The general operation of the unit is to evacuate the accelerating tube to approximately 10^{-5} mm Hg. Ionized atoms produced by the ion source are then accelerated down the accelerator tube by means of the difference of potential between the ion source and the target. When the beam hits the target, the nuclear reaction between the target material and the beam occurs, producting neutrons.

X-Ray Problem

Hydrogen ions (protons) are used for lining up the beam during initial studies, because no neutron-producing reactions are possible with protons and the accelerating potential available. This means that no neutron hazard exists; however, under these conditions there is a problem of x-ray generation. When the proton beam strikes residual gas in the accelerating tube, the target, or parts of the accelerating tube, it causes the release of electrons. The electrons are accelerated in a direction opposite to the proton beam and are finally stoped by colliding with parts of the accelerator. These electrons will have all energies up to the full accelerating potential of the machine and, when stopped, produce x-rays. The most intense x-ray field will be found near the high voltage terminal with the exposure rate depending on the

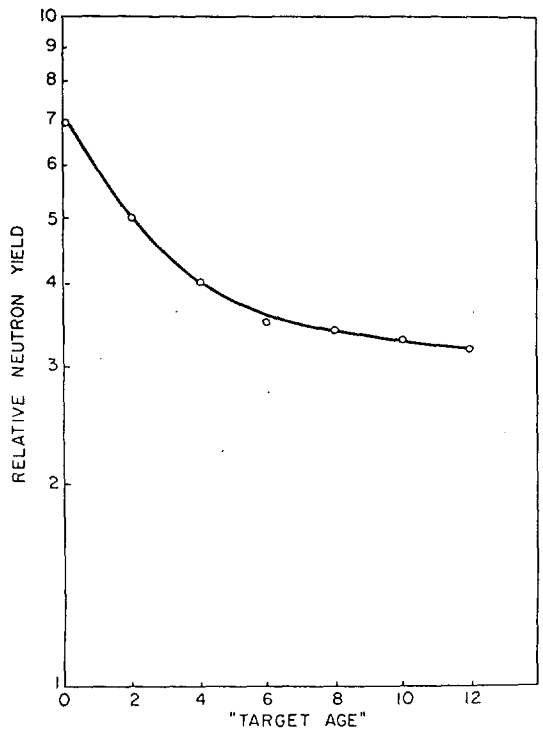

FIGURE 1. Relative neutron yield vs target age.

number of electrons released and the accelerating potential. Typical x-ray exposures are from 10 to 50 mr/hr at one meter from the high voltage terminal. Exposures, however, vary greatly, depending on conditions of beam focus and residual gas in the tube. To reduce the number of electrons accelerated down the tube, especially the large number released when the beam strikes the target area, a suppressor ring is located near the target. This ring is operated at –90 volts and forces electrons back to the target. Some care is required in making x-ray measurements around the ion source area because the source is operated by an RF generator, and many survey meters will give erroneous results when operated in an RF field.

Neutron Production

Neutrons may be produced by deuteron bombardment of many types of targets, but, with regard to maximum yield and energy available, the $H^2(H^3,n)He^4$ reaction presents the most difficult shielding problems. Yields of 4 x 10^{10} neutrons per second have been reported for the reaction.[1] At the present time, it is difficult to sustain such yields because of target deterioration or tritium loss. Figure 1 shows relative neutron yield versus target age. The slope of the curve may be decreased by reducing the beam current. This would result in a reduction in neutron production; for, to a first approximation, beam current is directly related to neutron yield. Recent improvements in target holder design, target construction, and target tritium content all promise either to increase neutron yields or extend target life. However, for the present, a yield of 4 x 10^{10} neutrons per second is considered "maximal" for purposes of shield design.

Permissible Exposure

Table I gives the flux for different neutron energies that would result in an average radiation guidance limit of 100 millirem per week being received, when 40 hours of exposure to the flux occurs per week. The guidance flux for 14-Mev neutrons is given as 10 n/cm²-sec. Because 14-Mev neutrons have the lowest guidance flux of neutrons capable of being produced by the machine and also have the greatest penetrability, the determination of the radiation protection requirements for the generator are based on these neutrons.

Flux Reduction

The greatest reduction in flux initially occurs because of the inverse square relationship of flux with distance. The flux of 3.18 x 10^9 n/cm²-sec at one centimeter for a yield

TABLE I
Maximum Permissible Neutron Flux
(Time-average flux for 40-hour week to deliver 100 mrems.)

Neutron Energy	*RBE*	*100 mrems*
Mev		*n cm⁻² sec⁻¹*
Thermal	3	670
0.0001	2	500
.005	2.5	570
.02	5	280
.1	8	80
.5	10	30
1.0	10.5	18
2.5	8	20
5.0	7	18
7.5	7	17
10.	6.5	17
10 to 30		[a]10

[a]Suggested limit.

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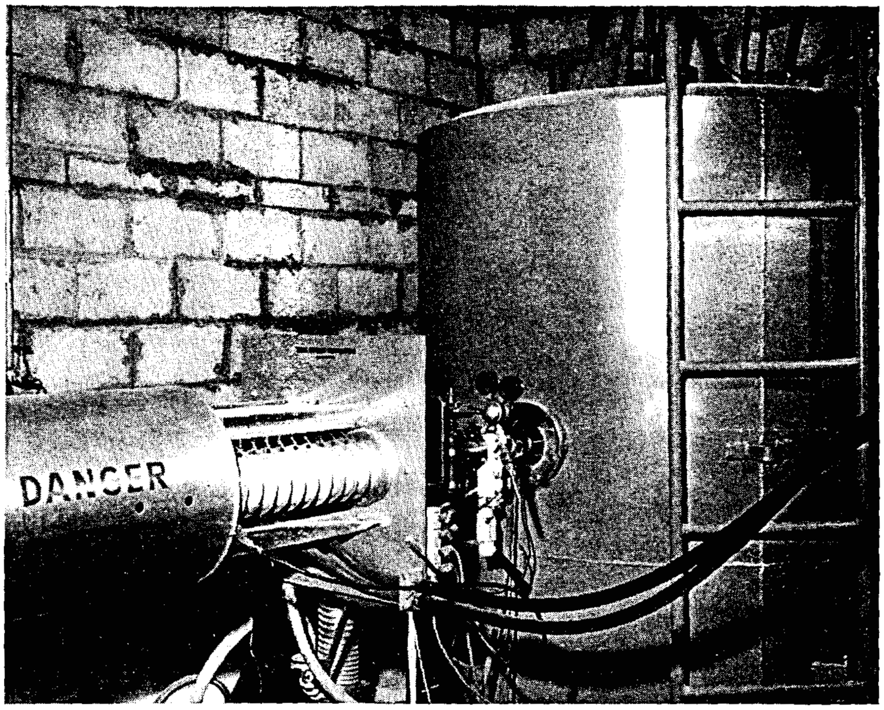

FIGURE 2. Moderator-shield tank and neutron generator.

of 4 x 10^{10} n/sec is reduced to 3.18 x 10^5 n/cm^2-sec at one meter by distance alone. Because the point of closest approach to the Oak Ridge Institute of Nuclear Studies (ORINS) generator during operation was planned to be limited to 12 feet, the flux without shielding at the point of closest approach would be 2.38 x 10^4 n/cm^2-sec. To reduce the flux to the radiation guidance limit, an additional flux reduction of 2.38 x 10^3 had to be provided. In reality, additional flux reduction is required because some lower energy neutrons resulting from scatter and degradation of energy will contribute to the exposure rate at the point of interest. The *NBS Handbook 63* suggests the use of a build-up factor of five for a condition not too unlike those encountered at the ORINS facility.[2] The neutron attenuation equation used to determine the thickness of material required to achieve the desired flux reduction was the exponential equation that uses neutron removal cross sections.

$$\Phi = \Phi_o B e^{-\Sigma_r x}$$

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where:

Φ = n/cm^2-sec
B = build-up factor = 5
Σ_r = removal cross section

The removal cross sections for 14-Mev neutrons in the materials used for calculating the shielding requirements for the ORINS facility are given in Table II.

TABLE II

Shielding Material	*Removal Cross Section*
Water	0.07 cm^{-1}
Steel	0.15 cm^{-1}
Concrete	0.075 cm^{-1}

Because it is possible to produce thermal neutron fluxes of 10^8 n/cm^2-sec with the generator by moderating the 14-Mev neutrons,[1] a water moderator-shield was used around the target. The moderator-shield consists of a water-filled steel tank 5 feet high and 5 feet in diameter. A 5-inch diameter aluminum tube has been built into the tank to permit placing the generator target at the tank's center (Figure 2). The approximately 27 inches of water surrounding the target

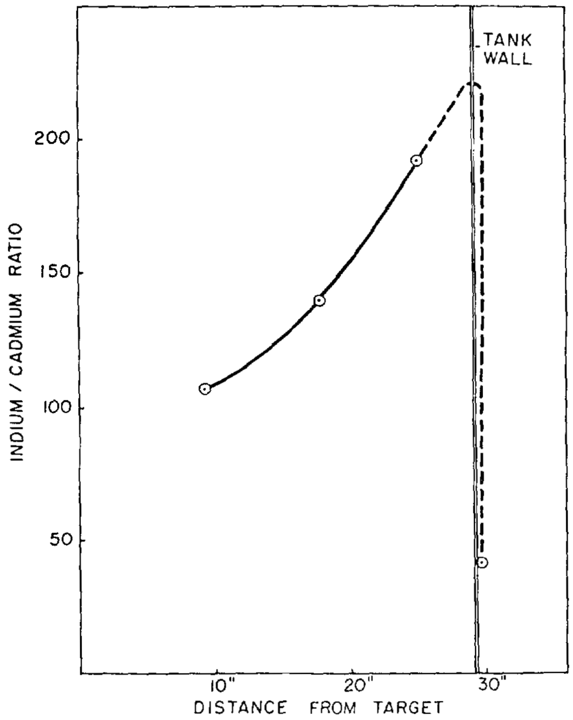

FIGURE 3. Effect of moderator and tank wall on thermal neutrons.

provides a reduction of flux of 2.1 x 10^2. The attenuation due to the thin steel tank wall was calculated to be negligible (less than 20%) and was neglected as of shielding value. The tank wall did reduce greatly the number of thermal neutrons escaping from the water moderator-shield as is shown in Figure 3. Additional shielding was provided by solid concrete blocks (137 pounds per cubic foot) as indicated on Figure 4. The minimum thickness of wall was 16 inches; hence minimum flux reduction of 2.2 x 10^1 could be expected. The total calculated flux reduction then amounted to 4.62 x 10^3, as compared to the required reduction of 1.12 x 10^4 when the build-up factor is considered. Because we did not anticipate that the generator would be operating 40 hours per week, we did not consider additional shielding necessary. Space was provided, however, for the addition of 16 more inches of solid concrete block in the future, if operating times are increased.

Concrete blocks were laid in the standard bricklaying fashion, except the mortar joints were solid rather than with voids as is common. No attempt was made to stagger joints, for we believed that the neutrons reaching the wall would not be traveling in any particular direction advantageous to streaming. Neutron measurements made after the wall was completed indicated that this was true.

A maze was constructed to prevent neutrons from coming directly out the entryway or from being scattered out the entryway (Figure 4). Because the size of the entryway would not permit the removal of the neutron generator and its power supply, a lintel was installed in the wall, and the solid blocks below the lintel were installed with soft mortar that will permit their removal and the removal of the generator from the room if necessary. To reduce the neutron exposure in occupied areas that would result from neutrons being scattered by the thin asphalt-type roof and from "sky shine," the shielding wall was made 11½ feet high to within one foot of the roof.

One direction, however, did not have full shielding. This area was directly behind the neutron generator. Neutrons leaving the target in the direction of the generator are not

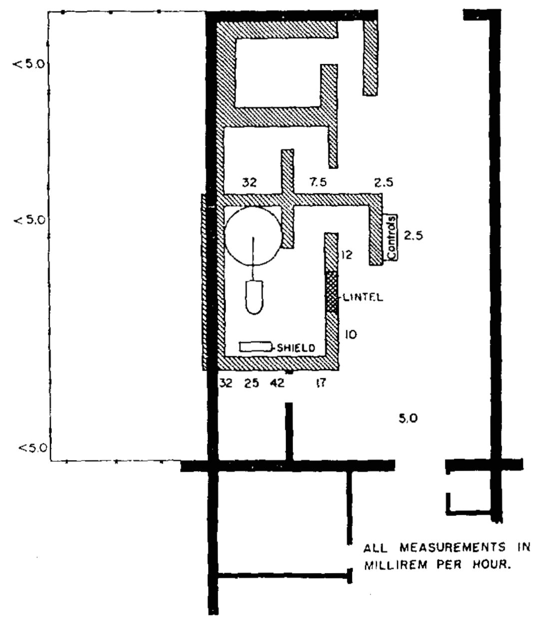

FIGURE 4. Solid concrete shielding wall indicated by cross-hatching. Upper cells used for gamma radiographic sources.

shielded by the water in the tank. Thus, fluxes encountered at the rear of the generator are higher than at the other positions around the generator. To correct this condition, a movable borated paraffin shield, 10 inches thick, was constructed. The shield was placed behind the generator high voltage terminal with care taken that its position does not permit a spark to occur between the shield and high voltage terminal. Placing the shield about 3 feet from the generator is adequate. The shield then intercepts the main portion of the neutrons that escape from the target in the direction of the generator.

Figure 4 shows the measured exposures around the neutron generator normalized for a yield of 4×10^{10} n/sec. Measurements were made with the Rad-san,[3] long counter, and activation methods. The shielding provided for this installation is obviously not adequate for a yield of 4×10^{10} n/sec and for a full 40-hour exposure week. It is not likely, however, that this facility or others like it will operate for such extended periods of time or will be able to sustain such high yields because of the problem of target life. Gamma radiation outside the shield during operation was less than 0.5 mr/hr.

Tritium Hazard

Because each target contains from 10 to 25 curies of tritium, a potential hazard may be expected to exist from the release of tritium from the target. During operation, tritium is released from the target and passed through the oil diffusion pump and fore pump and is exhausted to the atmosphere outside the building. Some tritium is trapped in the oil of the diffusion pump and fore pump and is released when these pumps are serviced. Urine samples collected from an individual who had one day earlier cleaned the diffusion pump in a well-ventilated hood had a concentration of 7.8 microcuries per liter. The maximum permissible urine concentration for continuous exposure is 28 microcuries per liter.[4] Previous urine analysis did not indicate tritium contamination, and no other cause of contamination is suspected. Tritium excretion after exposure followed that expected for a single exposure. Tritium exposure also occurs when targets are being changed. Personnel making the change have been measured to excrete 4.7 microcuries of tritium per liter of urine on the day after a target change. Supplementary local ventilation for target changes will soon be provided to help prevent the inhalation of tritium during target changes.

Summary

The radiation hazards from a neutron generator of the Cockcroft-Walton type are manifold; however, the prime hazard is from the neutrons produced by the machine. Neutron shielding requirements are dictated primarily by the $H^2(H^3,n)He^4$ reaction because of its high yield and the penetrability of the 14-Mev neutrons it produces. To reduce the neutron flux from a generator producing 10^{10} neutrons per second to acceptable levels for limited operation, 12 feet of distance that included 27 inches of water and 16 inches of solid concrete block were used.

The presence of x-rays produced by electrons accelerated in the evacuated tube in the direction of the target-to-ion source, even when neutrons are not being produced, requires that care be exercised in approaching the generator under these conditions.

Tritium released from the target was also noted to present an inhalation problem during maintenance work on the diffusion and fore pump and while changing targets.

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