A 14 MEV NEUTRON SOURCE CAPABLE OF DELIVERING A 1000 RAD DOSE UNIFORMLY OVER A 6 X 6-FOOT AREA

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Summary

This paper describes some aspects of a feasibility study[1] on a high flux, large area 14 MeV neutron generator. The purpose of this study was to provide a preliminary design of a 14 MeV neutron generator capable of uniformly delivering a 1000-rad dose to a 6 x 6-foot target. A source of about 2×10^{13} 14 MeV neutrons per second for four hours yields a 1000-rad dose with a uniformity of ten per cent to a 6 x 6-foot target located ten feet from the source. There are numerous charged particle reactions capable of yielding significant numbers of 14 MeV neutrons, but the requirement for mono-energetic 14 MeV neutrons precluded all reactions but the (d-T) reaction. The 14 MeV neutrons are produced by a 250 mA deuteron beam with 250 keV energy impinging on an 18-inch diameter tritiated-titanium target. The use of a large area tritiated-titanium target makes target cooling and depletion problems manageable.

NEUTRON PRODUCING REACTIONS

Numerous charged particle reactions can be used to produce 14 MeV neutrons. All but the $T(d,n)He^4$ reaction exhibit strong excitation of the higher states of the residual nucleus or in several cases, breakup of the deuteron or the compound nucleus. This leads to one or more lower energy neutron groups or a low energy continuum.

Due to the absence of excited states and the high threshold for breakup of the He^4 nucleus, the $T(d,n)He^4$ reaction produces mono-energetic neutrons at 14 MeV. The Q of the reaction is 17.6 MeV and the energy of the neutrons resulting from the absorption of zero energy deuterons is $E_o = 14.1$ MeV. When the deuteron has a kinetic energy < 0, the energy of the neutron is determined uniquely by its angle of emergence. The neutrons are emitted with energies $> E_o$ in the forward direction and with energies $< E_o$ in the backward direction. A thick target will degrade the energy of the deuteron beam and generates a small spread in energy of the emitted neutrons. When a 100-keV deuteron beam strikes a tritium target the energy of the neutrons emitted varies with the angle of emission from 14.8 MeV for neutrons emitted at 0° to 13.4 MeV for neutrons emitted at 180°; however the number of neutrons emitted per unit solid angle is approximately equal at all angles.

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The total cross section for the $T(d,n)He^4$ reaction has been measured by many investigators for energies from 8 keV to 10 MeV.[2-8] These data are shown in Figure 1.[9] The neutron yield from a thick target is calculated from the reaction cross sections, the rate of energy loss of deuterons in the target and the density of tritium in the target. The neutron yield as a function of deuteron energy from a 1:1 tritium-titanium loaded target is shown in Figure 2.[10]

The neutron yields from various reactions are shown in Table 1.[1] These yields are calculated for an equivalent target thickness of 1 MeV for all but the d-T reaction which was calculated for a thick Ti-T target with a 1:1 loading ratio and a deuteron energy of 250 keV. The cross sections of the d-T, d-D, and d-Li reactions are known at these energies, but the other cross sections were extrapolated from lower energy data.

Reaction	Yield neutrons/(sr - mA - sec) 14 MeV	Low Energy	Bombarding Energy (MeV)	Q (MeV)
$T(d,n)He^4$	1.25×10^{10}	None	.250	17.6
$D(d,n)He^3$	100×10^{10}	150×10^{10}	11	3.26
$Li^7(p,n)Be^7$	17×10^{10}	40×10^{10}	16	-1.64
$Li^7(d,n)Be^8$	$.72 \times 10^{10}$	4×10^{10}		15
$C^{12}(d,n)N^{13}$	5.3×10^{10}	40×10^{10}	15	-.281
$N^{14}(d,n)O^{15}$	7×10^{10}	70×10^{10}	9	5.1

Table 1

BEAM AND TARGET CONSIDERATIONS

The energy absorbed per gram of tissue for 14 MeV neutrons is 0.37 MeV/gram per neutron/cm^2, or 5.9×10^{-9} rad per neutron/cm^2. Thus an exposure of about 2×10^{11} neutrons/cm^2 is required to deposit 1000 rads in tissue. It can be shown that 2×10^{11} plus or minus ten per cent neutrons/cm^2 can be produced in four hours by a single neutron source emitting 1.4×10^{13} neutrons/second nine feet from a 6 x 6-foot target. It can also be produced by four neutron sources each producing 8.7×10^{11} neutrons/second arranged in a plane 3.5 feet above, below, to the left and to the right of the centerline of the target. The use of a single source uniformly irradiating the test specimen requires a geometry from which a large percentage of the produced neutrons are lost; consequently, it requires greater neutron production with its concomitant problems of greater heat dissipation and higher beam current.

The use of a multiple source system requires lower total neutron production than with a single source system. Hence, lower beam current and less cooling are required. However, uniformity of the radiation dose at the test specimen is more difficult to obtain because of a difficult geometry and probable changes in the output of the various sources as the targets deplete with age.

The calculations above do not take into account any loss of neutrons from scattering in the air or scattering in the neutron source itself. If an "effective removal" cross section σ_{rem}, which is slightly less than the total cross section and greater than the non-elastic cross section is used to calculate transmission losses then the required source strength in neutrons/second increases by about thirty per cent.

The largest factor determining the life of the target and yield of 14 MeV neutrons versus time is probably the depletion of the tritium from the target by replacement with deuterium. Other modes of target poisoning such as the build-up of a contaminant layer on the target face can probably be prevented. The loss of tritium by excessive heat can be minimized by adequate target cooling. The replacement of tritium by deuterium in the worst case would be a direct one to one replacement which would give a linear decrease in yield with time. It is probable that replacement is less severe. For example the rate of replacement of tritium by deuterium may depend upon the tritium concentration as well as the deuteron flux.

Experimental results indicate that the yield falls off to one-half of its initial value after approximately 600 μ amp-hours per cm^2 of target area for 250 keV deuterons and that in the 100 to 400 keV region the life of the target is approximately proportional to beam energy.[12] The value of 600 μ amp-hours/cm^2 can be related to the energy E of the deuteron by the relationship:

$$q_{\frac{1}{2}} = \frac{E}{250}\ 600\ \mu\ \text{amp-hours/cm}^2$$

or

$$q_{\frac{1}{2}} = \frac{E}{250}\ 2.16\ \frac{\text{coulombs}}{\text{cm}^2}$$

where $q_{\frac{1}{2}}$ is that charge which reduces the yield to one-half and is related to the charge q_e which reduces the yield to 1/e by $q_e = \frac{q_{\frac{1}{2}}}{.693}$.

If the target deteriorates at an exponential rate and the yield drops to $\frac{1}{e}$ of its initial value after a charge of q_e coulombs per cm^2 has been deposited on the target, the number of neutrons, dn, produced per cm^2 of target by a charge dq can be expressed as:

$$dn = k_E\ e^{-q/q_e}\ dq \qquad (1)$$

where $k_E = \left(\frac{dn}{dq}\right)_E$ is the initial neutron yield at an energy E. The total number of neutrons n_t produced per cm^2 by a total charge q_t per cm^2 of target is found by integrating equation (1) and is

$$n_t = q_e k_e \left(1 - e^{-q_t/q_e}\right) \qquad (2)$$

The total charge for a target with an area A required to yield n_t neutrons is given by:

$$Aq_t = -Aq_e\ \ln\left(1 - \frac{n_t}{q_e k_E}\right) \qquad (3)$$

The deuteron beam current is given by the total charge divided by the bombardment time, or:

$$i = \frac{Aq_t}{t} = \frac{-A}{t}\ q_e\ \ln\left(1 - \frac{n_t}{q_e k_E}\right) \qquad (4)$$

Using equation 4 and Figure 2 the values of beam current versus energy required to obtain 3 x 10^{17} neutrons in four hours are shown in Table 2.

E(keV)	$q_e\left(\frac{\text{coul}}{\text{cm}^2}\right)$	$k_E\left(\frac{\text{neutrons}}{\text{coul}}\right)$	$q_t\left(\frac{\text{coul}}{\text{cm}^2}\right)$	i(mA)
150	1.88	1 x 10^{14}	7.9	898
200	2.5	1.3	2.11	231
250	3.12	1.6	1.45	165
300	3.75	1.8	1.21	138

Table 2

It can be shown that the percentage of molecular ions strongly effects the required beam current and must be kept as low as possible. For instance, at 250 keV, a 20 per cent molecular beam requires a beam current of 223 mA and a 40 per cent molecular beam requires a 350 mA beam current.

If it is assumed that the tritium in the target is replaced by deuterium in such a way as to give a linear decrease in tritium control with time then Figure 3 shows depletion of neutron yield versus total accumulated deuteron beam current. Also shown in the figure are experimental points for yield from a zirconium-tritide target.[12] Figure 4 shows the neutron production versus time for several methods of tritium depletion for an 18-inch diameter target with an incident beam current of 250 mA of deuterons at 250 keV. The solid line shows a linear decrease based on a direct one-to-one replacement of tritium with deuterium. The dashed line shows a decrease in neutron production due to a replacement of tritium by deuterium at a rate dependent upon the tritium concentration. The upper dot-dash line is based on the optimistic assumption that the target with a one-to-one loading of tritium to titanium can absorb deuterium up to 40 per cent of the initial tritium concentration before starting to lose tritium by displacement.

The amount of titanium and tritium in the target assumed for the above life and yield calculations was that required to give a one-to-one ratio of atoms for a thickness equal to the depth of penetration of a 250 keV deuteron which was 1 mg/cm^2 of titanium and 0.61 c/cm^2 of tritium. For practical purposes twice this thickness should be used to insure against non-uniformity of tritium versus depth. Therefore, for a design thickness of 2 mg/cm^2 and 1.2 C/cm^2, the total quantity of titanium per 18-inch target would be 3280 mg and the total tritium would be 1970 curies.

A 250 mA beam at 250 keV delivers 62.5 kW of power to an 18-inch diameter target. If the current has a gaussian distribution at the target, the power concentration at the center of the target will be 88 watts/cm^2. This power is dissipated through a target backing material, which has a high thermal conductivity, to the cooling water which flows at high velocities thereby giving a high heat transfer coefficient. One possible target design contains a multitude of 3/16-inch diameter holes drilled through the beryllium copper backing parallel to the surface and spaced 0.060 inches from the surface and from each other. A flow of 124 gallons per minute through the cooling tubes can produce the necessary heat transfer coefficient and keep the surface temperature at about 100 °F.[13]

CONCLUSIONS

This neutron generator system generates 14 MeV neutrons through the T(d,n)He^4 reaction. It consists of a water-cooled titanium-tritide target which is bombarded with 250 keV deuterons from a duoplasmatron ion source. This neutron generator gives a total dose of 1000 rads in four hours to a 6 x 6-foot area located ten feet from the generator.

The equipment should be located in three rooms, the exposure room, the accelerator room and the mechanical equipment room. The exposure room which contains the test specimen is connected by a neutron channel to the accelerator room. The mechanical equipment room contains the cooling water equipment, the power supplies and the target preparation equipment.

The test specimen is located in the exposure room at a distance of about ten feet from the neutron source to insure a uniform irradiation of the specimen. The exposure room should be designed to minimize the background of lower energy neutrons which would give an undesirable contribution to the radiation dose. Much of the flux of neutrons from the target does not travel toward the test specimen but remains in the accelerator room from which it must be absorbed in the walls to prevent an excessive background flux of low-energy neutrons from traveling down the channel and striking the specimen.

The accelerator shown in Figure 5 consists of a high current duoplasmatron ion source based on an ion source developed and currently in use by Dr. E. Kelly at Oak Ridge National Laboratory a drift tube, a power supply, a vacuum system, and the target is a water-cooled titanium-tritide target. The water cooling system for the titanium-tritide target is a closed loop system cooled by a chilling unit. Any short-lived radioactivity induced in the cooling water is allowed to decay before leaving the exposure room by leaving it in a holding tank which is located inside the shielding enclosure. A ventilation system should maintain a negative pressure of about one half inch of water inside the shielding enclosure when the shielding door is closed. The radioactivity induced in the air surrounding the accelerator will be flushed out the stack instead of diffusing out into populated areas through cracks in the shielding.

References

1. "Feasibility Report on a High Flux, Large Area 14 MeV Neutron Generator", William M. Brobeck and Associates Report No. 118-1-R1.
2. Arnold, Phillips, Sawyer, Stovall and Tuck, Phys. Rev. 93, 483 (1954).
3. Conner, Bonner and Smith, Phys. Rev. 88, 468 (1952).
4. Argo, Taschek, Agnew, Hemmendinger and Leland, Phys. Rev. 87, 612 (1952).
5. S. J. Bame, Jr. and J. E. Perry, Jr., Bull Am. Phys. Soc. II, 1, 93 (1956).
6. A. Hemmendinger and H. V. Argo, Phys. Rev. 98, 70 (1955).
7. T. F. Stratton and G. D. Freir, Phys. Rev. 88, 261 (1952).
8. Brolley, Fowler, and Stovall, Phys. Rev. 82, 502 (1951).
9. N. Jarmie and J. D. Seagrave, LA-2014, (1957).
10. Ruby and Wilcox, Lawrence Radiation Laboratory Engineering Note (Aug. 10, 1956).
11. G. S. Hurst "Fast Neutron Dosimetry" in Fast Neutron Physics, Part I, J. B. Marion and J. L. Fowler, Editors, p. 825.

12. J. H. Coon, "Targets for the Production of Neutrons," in Fast Neutron Physics, Part I, J. B. Marion and J. L. Fowler, Editors. (Interscience Publishers, New York, 1961) p. 695.

13. Wm. H. McAdams, Heat Transmission, McGraw-Hill Book Company, Inc., New York and London (1942). p. 183.

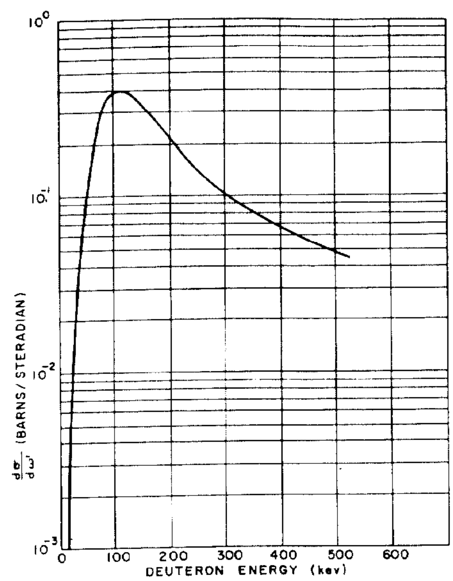

Fig. 1. Differential cross section for T(d,n)He reaction at 0.

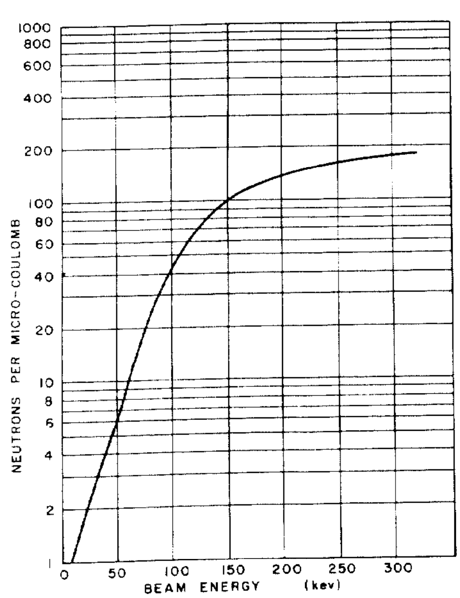

Fig. 2. Neutron yield for 1:1 loaded TI-T target.

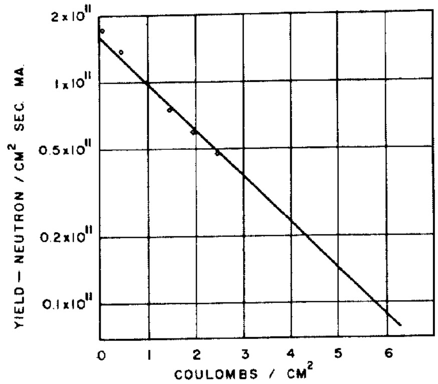

Fig. 3. Depletion of neutron yield.

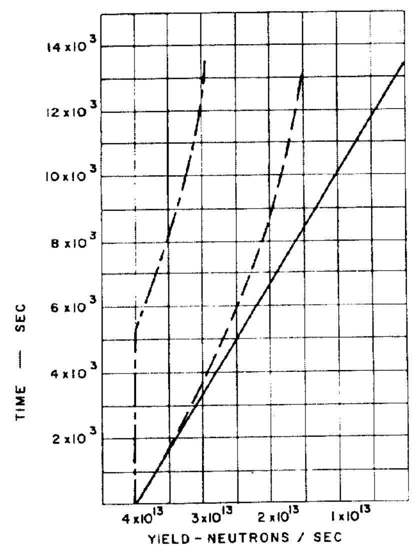

Fig. 4. Neutron yield vs time.

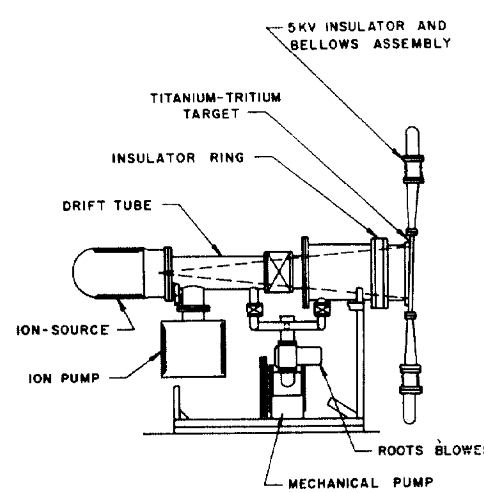

Fig. 5. 12 MeV neutron generator.