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The Irradiation Characteristics of the Test-type Hyper-thermal Neutron Generator for Neutron Capture Therapy

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INTRODUCTION

The neutron total cross section of water, which is a main component of human tissue, monotonously decreases from about 100 to about 40 barn as the neutron energy increases from thermal neutron region to nearly 0.5 eV, and it is almost constant to be about 40 barn from nearly 0.5 eV to nearly 100keV. Considering this energy characteristics of cross section of water, we proposed the application of the thermal neutrons shifted to higher temperature, namely higher energy, which we named "hyper-thermal neutrons", [1] for neutron capture therapy (NCT).

For the incidence of hyper-thermal neutrons with a few thousand K Maxwellian distribution, (i) the dose depth distribution of thermal neutrons is expected to be intermediate between thermal neutron incidence and epi-thermal neutron incidence, (ii) the neutron controllability is expected to be as good as that of the thermal neutron incidence, and moreover (iii) the contamination of fast neutrons is negligible level. So to speak, hyper-thermal neutron irradiation takes advantages of both thermal neutron irradiation and epi-thermal neutron irradiation.[2]

A TEST-TYPE HYPER-THERMAL NEUTRON GENERATOR

On the basis of the parametric survey results for high temperature scatterers and those sizes,[1] the design study for a hyper-thermal neutron generator was performed and a "test-type" generator

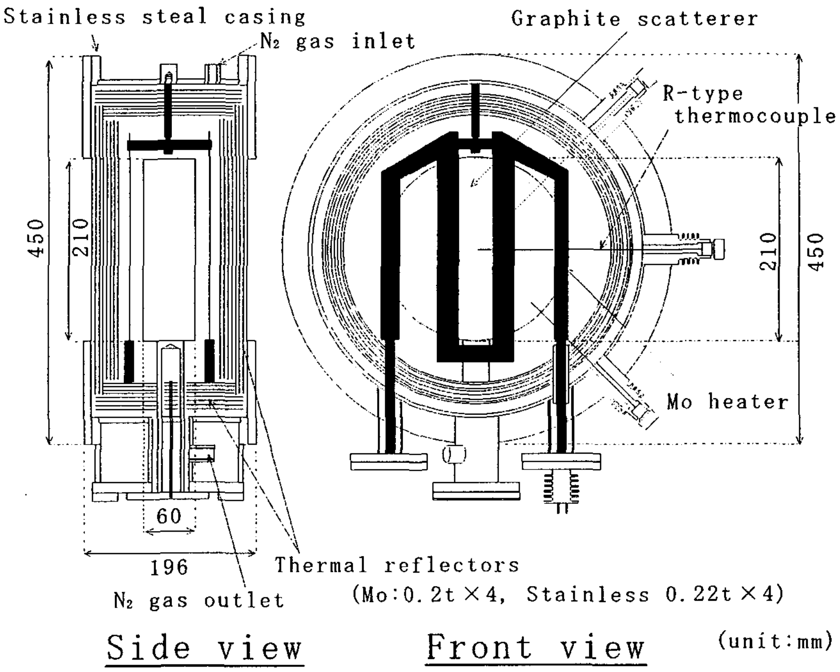

Figure 1. High temperature scatterer of the test-type hyper-thermal neutron generator.

Table 1. Outline of the test-type hyper-thermal neutron generator.

Available temperature	20℃ (293K, room temperature) - almost 1200℃
Irradiation field size	210mm diameter
Scatterer	Graphite of 60 mm thickness and 210 mm diameter Possible to replace with the other scatterer
Casing	Stainless steal (Outer size: 196 mm thickness, 450 mm diameter)
Control and heating method	Program controller (300℃/hr under the heating operation) Electric heating using Mo heaters (12kW)
Heat remove	Thermal reflection using Mo reflectors of 0.2mm thickness x 4 and stainless steal reflectors of 0.22mm thickness x 4 for one side Air-cooling using two fans
Heat measurement	Three R-type thermo-couples (Pt-Pt·1.3%Rh) 0 cm, 5 cm and 9 cm from the central axis
Cover gas	N_2 : 2.5 l/min under the heating operation 10 l/min under the cooling operation

was made for trial. The main design concepts were as follows; (1) the total size of the test-type generator, especially the thickness of the "path" for neutron beam, is as small as possible, using the structural material with low neutron-absorption, in order to obtain high neutron intensity. (2) the maximum attainable temperature is as high as possible, maintaining safety and controllability, of the heating system, and (3) the high temperature scatterer is selected from the viewpoint of safety-first.

Figure 1 shows the enlargement of the high temperature scatterer part of the test-type hyper-thermal neutron generator, and the outline of the test-type generator is summarized in Table 1. A graphite of 6 cm in thickness and 21 cm in diameter was selected as the scatterer from the standing-points of its stability at high temperature, simple handling and easy maintenance. Stainless steal was selected as main material for the structural frame and the casing. The outer size of the stainless casing is 19.6 cm thickness and 45 cm diameter, and the central part of 21 cm diameter, which corresponds to the irradiation field area (same as the scatterer area), is thin to be 0.2 mm. The inside of the stainless casing is filled with N_2 gas under the employment of the generator, in order to prevent the oxidization of the graphite scatterer. The N_2 gas also plays a role of cooling gas. The maximum attainable temperature is 1200 ℃ (almost 1500 K).

From the results of the heating-up tests of the generator, it was confirmed that there was no problem for thermal stability, controllability and safety at high temperature employment, and electrical power supply *etc.*. It was found that the differences among the temperatures at the three points in the high temperature scatterer were within 3%, and that the temperature at the center of the scatterer was stably attainable to be 1200 ℃.

IRRADIATION CHARACTERISTICS OF THE TEST-TYPE GENERATOR

3.1. Neutron Energy Spectrum

As one of the irradiation characteristics estimations for the test-type hyper-thermal neutron generator, the neutron energy spectrum dependent on the scatterer temperature was estimated by time-of-flight (TOF) method employing the neutron generator of the electron linear accelerator (LINAC) at Kyoto University Research Reactor Institute (KURRI).[3] At the KURRI-LINAC, neutrons are generated from (γ,n) reactions of the Bremsstrahlung X-ray at a tantalum metal target (water-cooled), and thermalized by the light water.

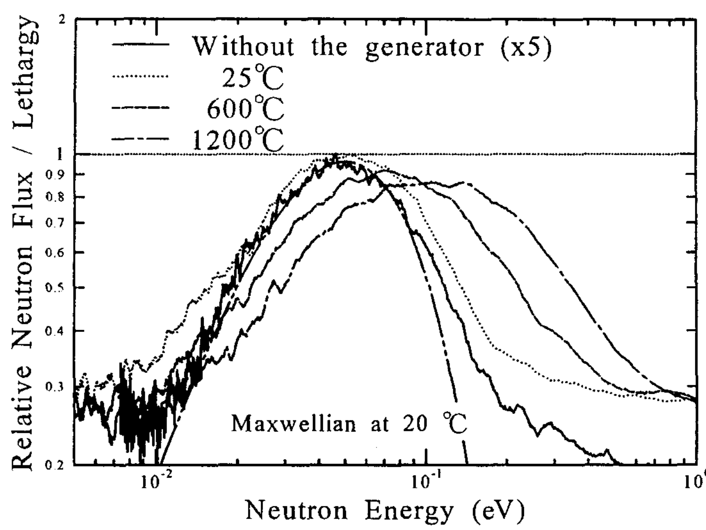

Figure 2. The relative comparison of the measured neutron energy spectra for the scatterer temperatures.

Figure 2 shows the obtained neutron energy spectra for the graphite scatterer temperatures of 25, 600 and 1200℃. The spectra are normalized to be 1 at the spectrum peaks for the scatterer temperature of 25℃. It is thought that the neutrons measured by the detector for the no-generator case consists mainly of the room-return neutrons from the walls of the target room. The neutron energy spectrum of this room-return component almost accords with a Maxwellian distribution of 20℃. The neutron energy spectrum shifts to the higher energy as the scatterer temperature is larger. The shape and peak energy of the obtained spectra were broader and lower comparing to a perfect Maxwellian spectrum. For the scatterer temperature of 1200℃, the obtained spectrum almost corresponds to the 800K Maxwellian spectrum, in regard to the most expected energy.

3.2. Thermal Neutron Dose Distribution

On the assumption of the application of hyper-thermal neutron irradiation to actual NCT, a phantom experiment was performed at the KUR Heavy Water Neutron Irradiation Facility (HWNIF) in order to estimate thermal neutron dose distributions in a water phantom.

Figure 3 shows the saturated activities of $^{197}Au(n,\gamma)^{198}Au$ reaction along the central axis of the water phantom (18 cm in diameter, 20 cm in length) for the graphite scatterer temperatures of 25, 600 and 1200 ℃. In the thermal neutron region, neutron absorbed dose distributions for brain tissue mainly depend on the reaction distributions of the 1/v materials such as $^{1}H(n,\gamma)^{2}D$, $^{14}N(n,p)^{14}C$, $^{10}B(n,\alpha)^{7}Li$ *etc.*. Also, the cross section of the $^{197}Au(n,\gamma)^{198}Au$ reaction accords to the 1/v energy characteristics below about 1 eV. So, Fig. 3 is thought to correspond to the neutron absorbed dose distributions in a water phantom. The peak position of distribution is deeper, the peak height is lower, and the distribution shape is more gentle as the scatterer temperature is higher. At the deeper than 2 cm, the distributions are almost the same. The controllability of hyper-thermal neutron incidence for the dose distribution in a human body can be confirmed. Assumed that the measured values are normalized at the peak position, the dose

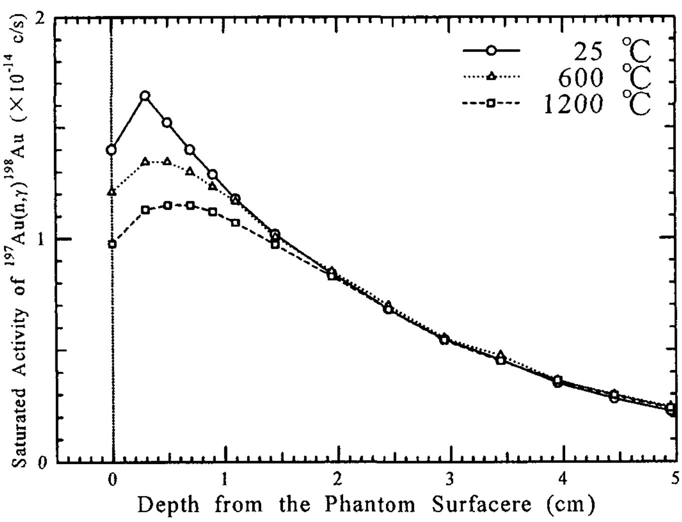

Figure 3. The depth distributions of saturated activity of $^{197}Au(n, \gamma)^{198}Au$ reaction along the central axis in a water phantom for the scatterer temperatures.

depth distribution is about 1 cm improved, comparing between the 25 ℃ scatterer and 1200 ℃ scatterer.

SUMARY

A test-type hyper-thermal neutron generator was designed and made for trial, on the basis of the fundamental study results mainly by simulation calculations. The prospect of the feasibility of the "hyper-thermal neutron irradiation field for NCT" was opened from the estimation results of the generator characteristics by the experiments at the KURRI-LINAC and KUR-HWNIF.

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