社会インフラ水分検出用可搬型線形加速器駆動中性子源の開発

DEVELOPMENT OF MOBILE LINAC-DRIVEN NEUTRON SOURCE FOR MOISTURE INSPECTION OF SOCIAL INFRASTRUCTURES

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Abstract

The existing non-destructive inspection method employed for concrete structures uses high energy X-rays to detect internal flaws in concrete structures and iron reinforcing rods. In addition to this conventional method, the authors are developing an innovative inspection system that uses a mobile compact linac-driven neutron source that utilizes neutron backscattering, to measure the moisture distribution in concrete structures and estimate the corrosion probability distribution of iron reinforcing rods.

1. INTRODUCTION

During the period of rapid economic growth from the 1950s to the 1970s, the Japanese governmental investment in infrastructural projects such as bridges and buildings expanded rapidly. However, most of the industrial and social infrastructure projects had an estimated lifetime of approximately 50 years only, so the declining strength of concrete structures has become an issue of national importance. From a cost-performance point of view, it is better to carry out on-site nondestructive inspections regularly and repairs as and when needed, rather than demolishing or rebuilding them. Non-destructive inspection methods for social infrastructures, aimed at detecting internal flaws in concrete structures and iron rods, have therefore been developed [1].

In addition to the conventional high energy X-ray method, the development of a neutron backscatter moisture detection system using a linear accelerator driven neutron source to measure moisture distribution in concrete structures is now under development. By combining the knowledge of the moisture distribution in concrete structures with the DuCOM_MC (DuCOM for Material Characteristics) system [2], which is the complete simulation & analysis code for concrete structures, the corrosion probability distribution of iron reinforcing rods can be estimated.

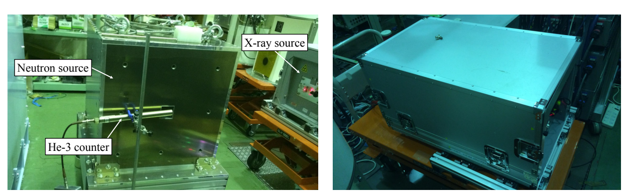
Since the neutron scattering cross-section of water is significantly greater than that of concrete over a wide range of neutron energy levels, moisture detection in concrete structure can be conducted effectively by detecting moderated thermal neutrons. Our combined high energy X-ray inspection system and the neutron moisture detection system will comprise an innovative inspection system that not only detect existing internal flaws in concrete structures but can also predict future structural degradation. This research paper reports progress in the development of a mobile X-band 3.95 MeV electron linac-driven neutron source for the on-site nondestructive moisture inspection of concrete structures.

2. DESCRIPTION OF NEUTRON SOURCE

2.1 Development of mobile electron linac-driven neutron source

Beryllium $\left(^{9}\mathrm{Be}\right)$, having the lowest threshold energy for photo-nuclear reaction $^{9}\mathrm{Be}\,(\gamma,\ \mathrm{n})\,^{8}\mathrm{Be}^{*}$, is used in a mobile linac-driven neutron source, as an Italian group developed in the previous study [3]. For the prototype, a beryllium photo-neutron target has been combined with a graphite reflector layer, a boric acid resin layer for neutron shielding, and a lead layer for γ-ray shielding (Figure 2). The $^{9}\mathrm{Be}$ target and the 3.95 MV mobile X-ray source together comprise the mobile neutron source system (Figure 1). Optimization of the beryllium target size and neutron/γ-ray shielding simulation are performed using the *PHITS* [4] Monte-Carlo code.

The calculated neutron yield in the prototype neutron source is $2.79 \times 10^{5}\ \mathrm{n/s}$. Considering the neutron yield of $1\ \mu\mathrm{g}$ of $^{252}\mathrm{Cf}$, approximately $2.0 \times 10^{5}\ \mathrm{n/s}$, the prototype neutron source is as intense as the $^{252}\mathrm{Cf}$ neutron moisture gauge.



(a) Neutron source target station. (b) Mobile X-ray source.

Figure 1: Neutron source system of the University of Tokyo.

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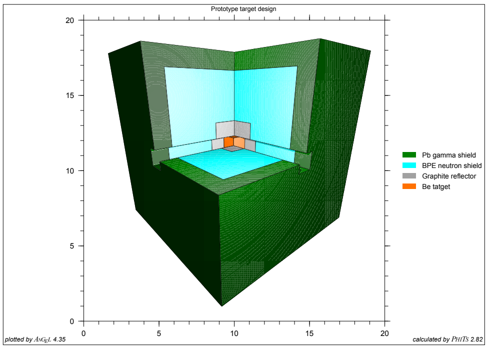
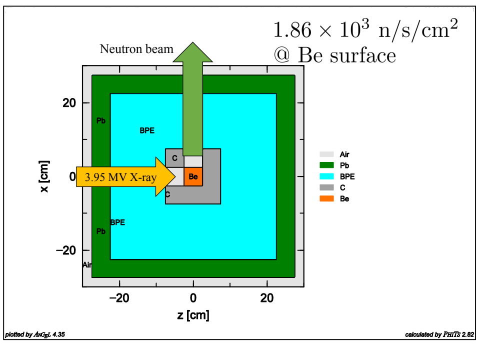


(a) Outline of target design.

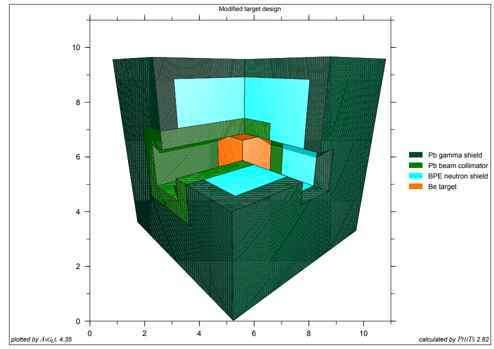


(b) Neutron target design (top view).

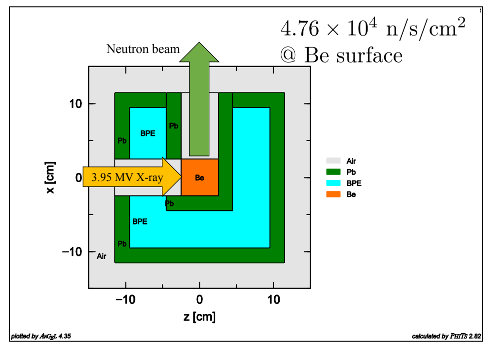
Figure 2: Prototype neutron target design.

Although the prototype neutron source successfully detected moisture in concrete structures[5], the heavy weight of the target and the long detection-time are problematic. In order to perform moisture detection more rapidly and with a better signal-to-noise (S/N) ratio, several modifications to the design of the system have been considered. In particular, if unnecessary shields of the target are removed, the distance between the X-ray source and the beryllium target is reduced and the neutron flux at the exit of the target beam line increases. In the modified design, the graphite reflector layer is replaced with a lead beam collimator since mainly fast neutrons are used in the neutron source, a beam line using a high-Z material that does not moderate the neutrons is better (Figure 3).

The calculated neutron yield in the redesigned neutron source is 7.13×10^6 n/s, an increase by a factor of 10 compared with the former design of the neutron source (Table 1). The target weight is then reduced to 70 kg, which is much more manageable than the target design of the prototype, which was 1500 kg. Radiation safety is still satisfactory even with the reduced target shielding.



(a) Outline of target design.



(b) Neutron target design (top view).

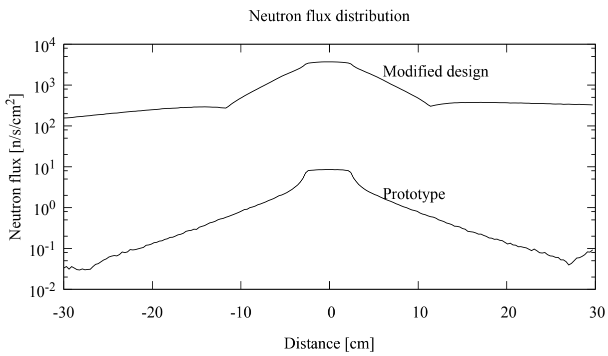
Figure 3: Modified neutron target design.

Table 1: Comparison of Prototype and Modified Design of the Neutron Source

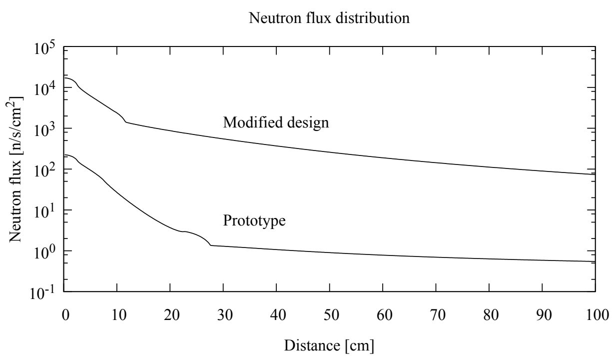
	Prototype	Modified	
Total yield	2.79×10^5	7.13×10^6	(n/s)
Flux	1.86×10^3	4.76×10^4	(n/s/cm^2)
Weight	1500	70	(kg)

2.2 Neutron production

The comparison of neutron flux between prototype neutron source and modified neutron source is shown in Figure 4. As shown in Figure 4a and 4b, the neutron flux of modified design target is higher by factor of 100 compared to prototype target at target surface, and along the neutron beam line.



(a) Neutron flux distribution along lateral direction at neutron target surface.



(b) Neutron flux distribution along neutron beam line.

Figure 4: Comparison of neutron flux distribution between two designs.

3. MOISTURE DETECTION USING BACKSCATTER NEUTRON

3.1 Preliminary experiment using existing neutron gauge

An preliminary experiment using neutron moisture gauge *Suikoden* [6] was conducted (Figure 5). *Suikoden* uses 0.1μg of ^{252}Cf as neutron source and ^{3}He proportional counter as neutron detector. *Suikoden* has detected 250g of moisture under an 7cm thick concrete sample in 20 seconds with 3σ of significance level (Figure 6).

Figure 5: Moisture detection experiment using neutron moisture gauge.

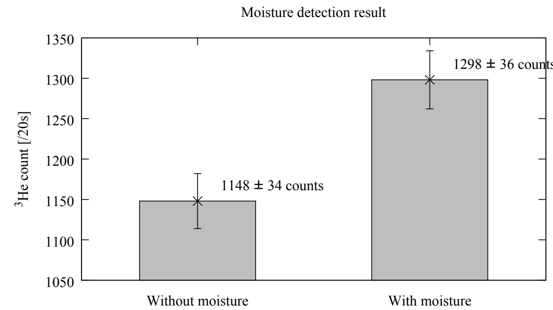
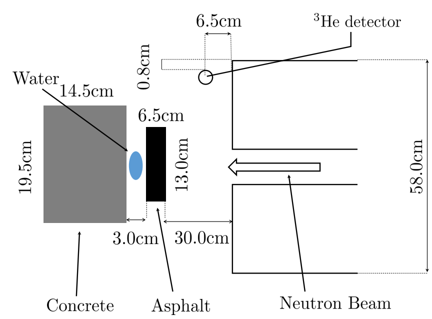


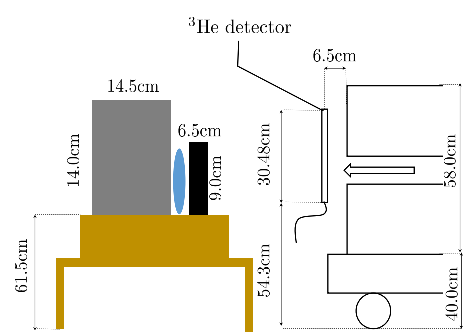
Figure 6: Moisture detection experiment result using neutron moisture gauge.

3.2 Experiment using prototype neutron source

The experiment for moisture detection in a concrete structure was conducted using the prototype mobile linac-driven neutron source (Figure 7). 50g of water under a 7 cm thick asphalt sample was detected with a confidence level of 1σ in 600 seconds at a distance of 30 cm (Figure 8).



(a) Top view.



(b) Side view.

Figure 7: Moisture detection experiment set up.

3.3 Discussion

The effectiveness of the moisture detection of concrete structure with backscatter neutron was proved in the experiment using neutron moisture gauge *Suikoden*. However, the efficiency of the prototype linac-driven neutron source

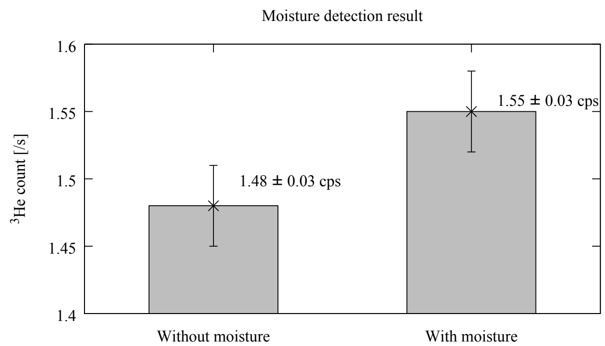


Figure 8: Result of water detection experiment in concrete structure (count per second).

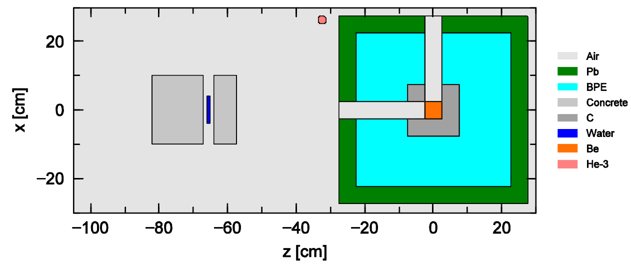
was insufficient for moisture detection with a high S/N ratio. The statistical significance of moisture detection was 1σ in the experiment. For more significant results, for example, 3σ of significance, the detection time would have been approximately 2200 sec according to the numerical calculation.

The moisture detection using modified neutron source was simulated. Firstly, the efficiency of the modified design and the prototype one was compared (simulation geometry shown in Figure 9). Table 2 shows the comparison of estimated moisture detection time for moisture detection with 3σ significance using former and latter design. As we can see, moisture detection time is shortened by factor of 10 using the modified neutron source.

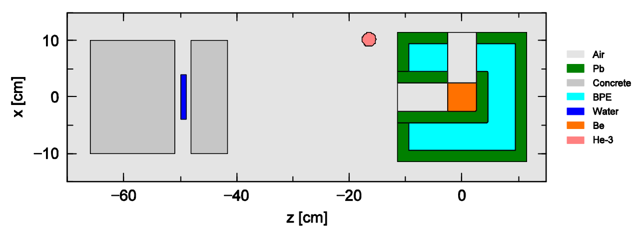
Table 2: Comparison of Detection Time (3σ)

	Prototype	**Modified**	
Detection time	2200	250	(sec)

The modified design and the existing neutron moisture gauge *Suikoden* is also compared. Since the distance between moisture gauge and concrete sample was 0cm in the experiment using *Suikoden*, the distance between the neutron source and the sample is set as close as possible (Figure 10). Table 3 shows the comparison of the experiment result of the moisture detection time of *Suikoden* and the calculated one of modified design neutron source. The detection time using modified neutron source is shorter than *Suikoden* by factor of 10, noting that the amount of detected moisture in experiment using linac-driven neutron source is one-fifth of that in experiment using *Suikoden*. From this result, the modified neutron source can be considered to be more efficient compared to the existing neutron moisture gauge.



(a) Moisture detection using prototype design neutron source.



(b) Moisture detection using modified design neutron source.

Figure 9: Moisture detection simulation geometry.

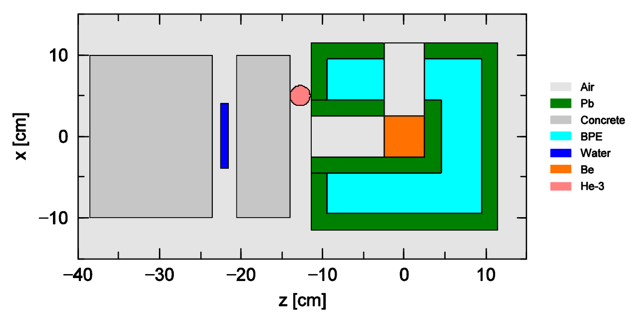


Figure 10: Moisture detection simulation geometry.

4 . SUMMARY AND SUBJECTS

We developed and tested a mobile linac driven neutron source. The prototype neutron source succeeded in moisture detection in real concrete sample, however, the detection time and its weight was a problem. We modified the prototype design, reducing its size, and performed numerical computation and verified the modified design can perform more efficient moisture detection compared to our former neutron design neutron source.

As the future work, the actual experiment of moisture detection using mobile electron linac-driven neutron source at Myoko Ōhashi will be conducted in 2017, and

Table 3: Comparison of Detection Time (3σ)

	Suikoden (250g water)	Modified (50g water)	
Detection time	20	1.5	(sec)

therefore furthermore improvement of neutron source is required. Figure 11 shows the simulation geometry of the moisture detection inside 0.1cm thick iron sheath under 20cm of concrete.

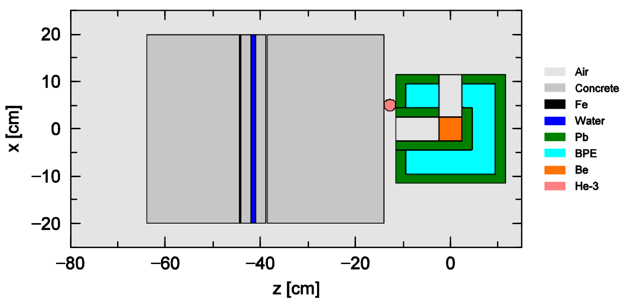


Figure 11: Moisture detection simulation geometry.

From the simulation result, the detection time is estimated to be 2000 $\sim$ 3000 seconds assuming the moisture having 1cm of diameter, however, the computation and comparison under various condition should be proceeded.

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