Bull. Tokyo Univ. For., 93, 13–19 (1995)

Water Distribution Inside the Woods by Neutron Radiography

Tomoko M. NAKANISHI* and Sadamoto WATANABE**

Introduction

Though neutron radiography (NRG) was used widely in industrial field as non-destructive analyzing method, namely for investigating the inside structure of an airplane or fuel tank, there are not so many applications for plant research (HAINSWORTH and AYLMORE, 1986; ADERHOLD *et al.*, 1989), at least none in Japan. One of the reason is that NRG requires high neutron flux, which restricts the available neutron source (BERGER, 1965; GARRETT *et al.*, 1977). Though using an accelerator or highly active radioisotopes is one of the candidates for beam, homogeneous thermal neutron beam is necessary for plant samples to perform NRG. Therefore the most desirable neutron source is that from an atomic reactor. Another restricting condition is that considerably large irradiation field with the uniform neutron flux is needed. Recently, JRR-3M, an atomic reactor at Japan Atomic Energy Research Institute has been remodeled and a special thermal neutron outlet aiming to perform neutron radiography has been set up. Therefore, the authors tried to use the facility to perform NRG for plant samples.

The principle of NRG is the same as X-ray radiography or radioautography using radioisotopes. However in the case of NRG, the reactions of neutrons to the elements in the sample are different from those of X-ray or γ-ray, therefore, NRG provides us completely different information. The neutron attenuation coefficient is distinctively larger for light elements, such as H or B, and for some of the rare earth elements (Fig. 1). In other words, we can select the specific element to be visualized by neutron beam. When thermal neutron is irradiated to plants, the image of H distribution can be obtained. However, since the major part of the plant cells, more than 80%, is consisted of water, the image of H represents water distribution in the plants. When the water content was comparatively small, such as the center part or completely dehydrated portion of wood, not only water but also the components containing H are superposed to water in the image.

To get the high resolution of the image, the improvements of n/γ converter and film are essential. Since it is difficult to find any report about the suitable converter and film system for plant research, the authors used gadrinium converter and a special type of X-ray film, as we reported earlier (NAKANISHI *et al.*, 1991a, 1991b, 1992a, 1992b, 1993). The converter converts the neutrons, after penetrating the plant samples, to γ-ray, with which the X-ray film is exposed to provide the image. The darkness of the image corresponds to the water content in the sample. With JRR-3M reactor facilities and the method we selected, the resolution of the image in the X-ray film was found to be about 15 μm, which was mainly restricted by the nature of the converter.

In the case of plant samples, the water distribution in the root as well as in the surrounding soil, during the root development, was able to be visualized by NRG (NAKANISHI *et al.*, 1992a, 1992b, 1993). Also NRG was proved to be a powerful method to know the water distribution in the upper part of the plant, non-destructively. The essential point of

* Faculty of Agriculture, Univ. of Tokyo.
** Present address: University Museum, Univ. of Tokyo.

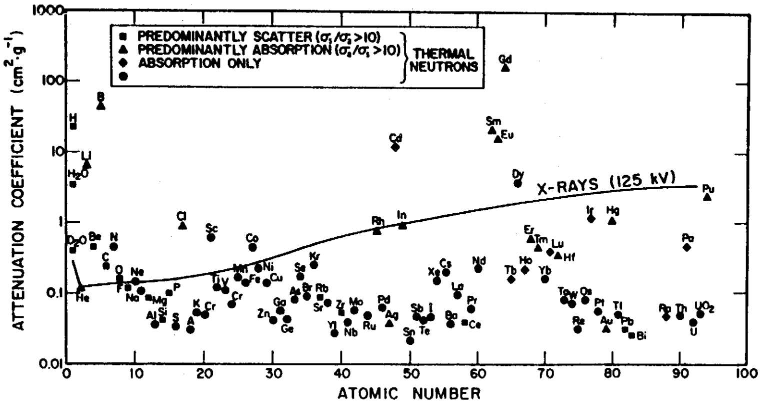


Fig. 1. Neutron attenuation coefficient. (GARRETT, 1977).

NRG for the plant research is that the method provides not only the distribution of water in plant, but also the morphological changes of the plant tissue itself, since every tissue contains enough amount of water to be appeared in the image. Theoretically, when the cold neutron source comes to be available in the future, the resolution of the image could be higher in one order. In other words, the water image inside the single plant cell might be able to be visualized.

Thus NRG is expected to open the new plant research field. This research is one of the application of the promising method.

Materials and Methods

Five kinds of woods, *Pinus thunbergii* Parlatore, *Metasequoia glyptostroboides* Hu et Cheng, *Chamaecyparis obtusa* Endl., *Quercus serrata* Thunb. ex Murray and *Robinia pseudoacacia* L. were used, ages of which were 18, 10, 19, 18 and 8 years old, respectively. All the trees were grown in the Experimental Station at Tanashi, the Tokyo University Forest, University of Tokyo. About four hours before performing NRG, all the trees were felled and the logs of 80 cm in length were prepared from the portion of 1 m to 1.8 m above the ground. Then the wood stem samples were carried to Japan Atomic Energy Research Institute, where the discs about 1 cm, 2 cm and 3 cm thick were cut from each sample tree by a chain saw just prior to the neutron irradiation. The diameters of wood discs were, 13.5 cm, 13.2 cm, 12.3 cm, 16.5 cm and 12.3 cm for *Pinus thunbergii*, *Metasequoia glyptostroboides*, *Chamaecyparis obtusa*, *Quercus serrata* and *Robinia pseudoacacia*, respectively.

The irradiation was carried out at the NRG outlet of JRR-3M atomic reactor, installed at Japan Atomic Energy Research Institute. A schematic outlet of the NRG chamber is shown in Fig. 2. To get the image, a wood sample was fixed to the cassette one by one with an aluminum tape, where a gadrinium converter (25 μm, in thickness) and an X-ray film (Kodak, SR) were sealed in vacuum. Then the cassette with the sample was set vertically in the chamber and was exposed to the thermal neutron for 19 seconds. The total flux was 8.7×10^7 n/cm^2. After the irradiation, the cassette became radioactive due to the γ-rays from ^{28}Al, produced by (n, γ) reaction. However, because of its short half-life of ^{28}Al (2.3 min), the activity of the sample was decreased rapidly. It took about ten minutes to cool down the sample for successive processing. After developing, the film was scanned by a scanner and the image was converted to a positive one. Special care is necessary for the development of the films. They had to be stood still during the development and fixing, in each solution,

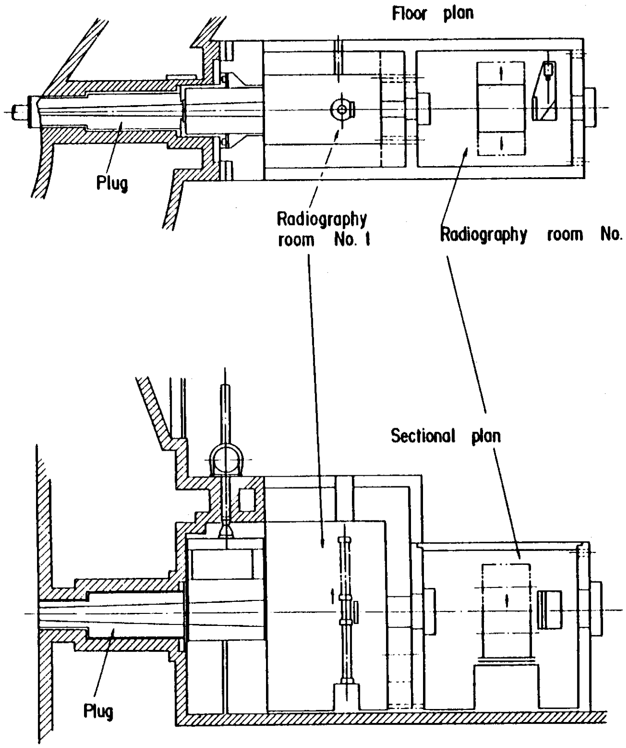


Fig. 2. NRG facility of JRR-3M at Japan Atomic Energy Research Institute.

otherwise noise in the image appeared.

Results and Discussion

Figure 3 is the photograph of wood stem discs with 1 cm thickness. The NRG image corresponding to Fig. 3 is shown in Fig. 4. In each image a brighter part corresponds to the one containing much water and a darker part represents the water deficient one. All the images show water distribution in wood discs, not water movement. In Figures, 3 and 4, (a), (b), (c), (d) and (e) correspond to *Pinus thunbergii*, *Metasequoia glyptostroboides*, *Chamaecyparis obtusa*, *Quercus serrata* and *Robinia pseudoacacia*, respectively. Though NRG was performed for three kinds of discs for each wood, different in thickness, only the images of the thinnest one, 1 cm in thickness, were shown. In every case, the thicker sample did not provide the image with high resolution and sometimes even the shape of the annual ring could not be observed, because of high water content. For all the discs tested, the thinner the sample, the higher the contrast of the image.

The NRG image of *Pinus thunbergii* (Fig. 4a) showed heterogeneous water distribution within the same annual ring, which distinguished the width of each annual ring. The width was comparatively large at first several years and then became gradually narrow, year by year. Water seems to be distributed sometimes across the annual ring, especially at the lately developing part. The image also showed some ray spread out from the center. The distinctively dark part in the pith indicates the decrease of water or H containing components, suggesting the beginning of the necrosis of the tissue at the center.

The NRG image of *Metasequoia glyptostroboides* (Fig. 4b) gave two distinctively differ-

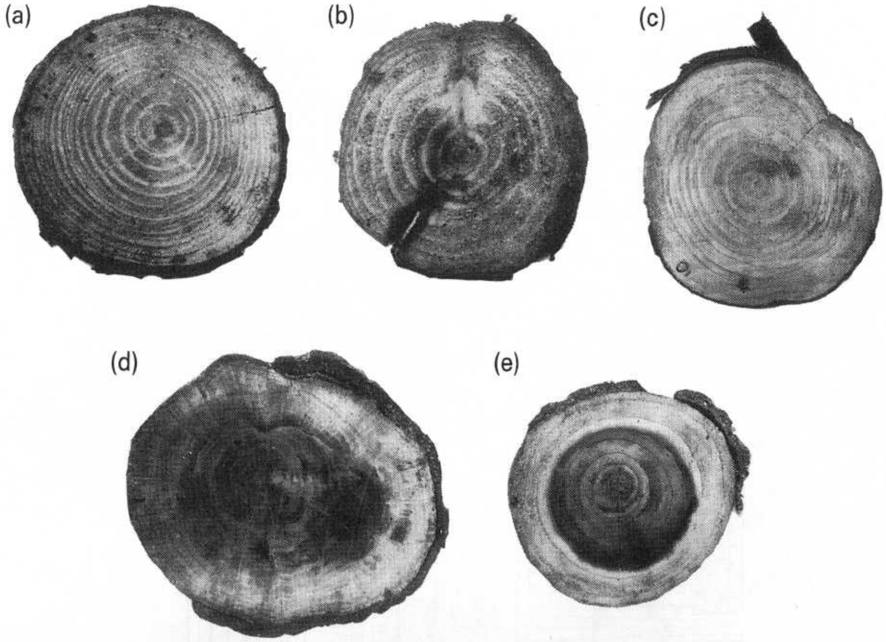


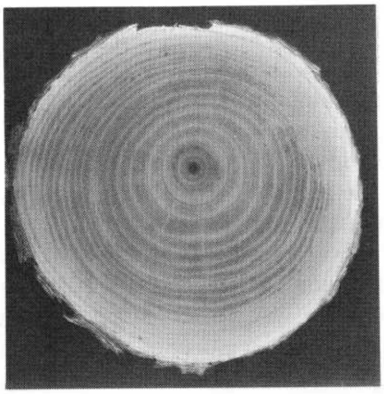
Fig. 3. Photograph of wood slice samples irradiated.
(a): *Pinus thunbergii*, (b): *Metasequoia glyptostroboides*, (c): *Chamaecyparis obtusa*, (d): *Quercus serrata*, (e): *Robinia pseudoacacia*.

ent parts of water content, though from the optical photograph (Fig. 3) they were not observed (Fig. 3). The NRG image also shows that water is distributed mainly at several lately growing layers and only little water seems to be left at center part. In this sample, heterogeneous water distribution was also shown, both within and across the annual ring. The water content was the highest in the latest ring, which was shown by distinctively white color in the image. Black line penetrating the annual ring is the part where the big branch was grown, close to this place.

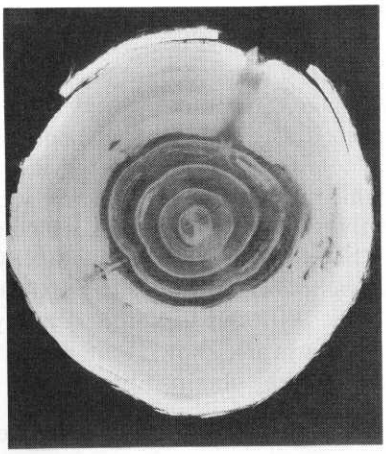
In the case of *Chamaecyparis obtusa* (Fig. 4c), water did not distribute along with the annual ring in the part, near the bark. The distribution showed some waving pattern, which sometimes spread across several stem growth. Besides the large white image at the outer part of the slice, a lot of white rings were shown at the inner part, which could not be attributed only to water. As cited above, water as well as some components containing H atom are shown as the image. However, distinctively white clotting parts shown at several stem growth year are estimated to be due to the water distribution. Waving pattern of water image, independent to the annual ring might indicate some chemical interaction across the ring. It is known that the heartwood, as far as indicated by the color change, is not necessarily formed along with the annual ring, which might be explained by the water distribution across the ring.

Quercus serrata showed the highest content of water or H containing components when compared to the other wood samples tested (Fig. 4d). The NRG image was white in almost all the parts. Though the highest water content was observed near the bark, the water distribution pattern was hardly able to be recognized. The annual ring was discerned from the water deficient part, shown as black dots. When scanned from bark to heart, there was no uniform change of the darkness and some peaks of white part were observed. However

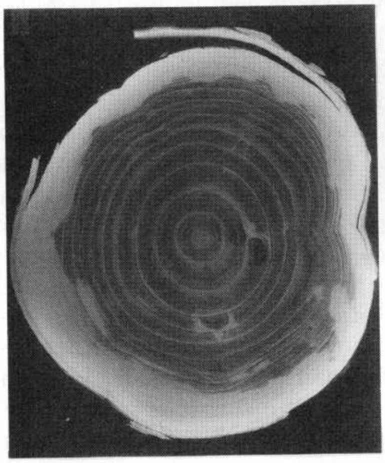
(a)



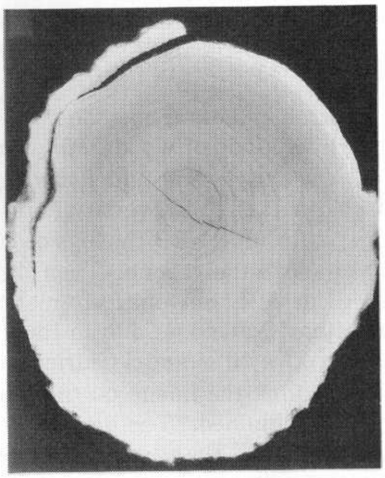
(b)



(c)



(d)



(e)

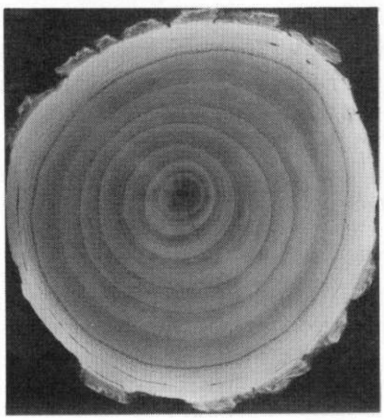


Fig. 4. NRG image of the wood slice samples.
The thickness of each sample was about 1 cm.
(a): *Pinus thunbergii*, (b): *Metasequoia glyptostroboides*, (c): *Chamaecyparis obtusa*, (d): *Quercus serrata*, (e): *Robinia pseudoacacia.*

relatively higher amount of water seemed to be distributed in the lately developed part.

Robinia pseudoacacia gave another interesting image (Fig. 4e). The heart wood, which was clearly observed by a photograph (Fig. 3), was not shown in the NRG image. In the NRG image the content of water and H containing components seemed to be the same in heartwood as well as in sapwood. Water was distributed mainly in the last annual ring. Black dots are the vessel where water was to be introduced. From the image summer wood contains more water than spring wood. Inside the 2nd, 3rd and 4th annual ring, a few growth layers were observed, which reflect the weather change in those years.

This is the first trial to obtain NRG image of the wood stem. As is shown in the figures, NRG was shown to be able to visualize water distribution in the wood stem, especially near the bark. With this technique, the drying process of the wood is expected to be studied in detail. It was also shown that, not only water image but also morphological change of the tissue, could be obtained by NRG.

Acknouwledgement

The authors express their sincere thanks to Mr. Tsuruno, at Japan Atomic Energy Research Institute, with useful discussion and the arrangement to use JRR-3M facilities.

Summary

Neutron radiography (NRG) was applied to know the water distribution inside the wood. Five kinds of woods, *Pinus thunbergii*, *Metasequoia glyptostroboides*, *Chamaecyparis obtusa*, *Quercus serrata* and *Robinia pseudoacacia*, grown in the Experimental Station at Tanashi, the Tokyo University Forest, were used for the measurement. About four hours before performing NRG the logs of 80 cm in length were prepared from the portion of 1 m to 1.8 m above the ground. Then the wood samples were taken to the atomic reactor and further cut to about one centimeter thickness just prior to the neutron irradiation to prevent any water loss due to the evaporation. Each sample was fixed to a cassette, in which an X-ray film and a gadrinium converter were sealed in vacuum. After developing the X-ray film, the image on the film was scanned and the water distribution inside the wood was obtained. The degree of the darkness in the image corresponded well to the water content in the sample. The resolution of the image was found to be about 15 μm. Though the highest water distribution was observed, as expected, near the bark, it was shown that its distribution was not necessarily along with the annual ring. In the case of *Robinia pseudoacacia*, a few stem growth layers within an annual ring were also observed by NRG. Interestingly, the water content at the heartwood seems to be the same as sapwood, whereas from the optical image, the formation of heartwood was clearly observed. This is the first trial to obtain the real time water image in a wood sample, using NRG. NRG was shown to be a promising method to analyze the water movement inside the wood as well as the morphological difference of the tissue.

Key words: Neutron Radiography, *Pinus thunbergii*, *Metasequoia glyptostroboides*, *Chamaecyparis obtusa*, *Quercus serrata*, *Robinia pseudoacacia*

References

ADERHOLD, H. C., BOULDIN, D. R., RIHA, S. J. and CAHN, M.: Investigation of the Root-Soil System with Neutron Radiography. Proc. of The 3rd World Conference on Neutron Radiography, May 14–18, Osaka, Japan, pp. 1–7, 1989.

BERGER, H.: Neutron Radiography, methods, capabilities and applications. Elsevier publishing Co., pp. 146, 1965.

GARRETT, D. A., BERGER, H.: The Technological Development of Neutron Radiography. Atomic Energy Review **15**, 125–142,1977.

HAINSWORTH, J. M. and AYLMORE, L. A. G.: Water Extraction by Single Plant Roots. Soil Sci. Soc. Am. J. **50**, 841–848, 1986.

NAKANISHI, T. M., MATSUMOTO, S. and KOBAYASHI, H.: Non-destructive Analysis of Rape Plant Pod by Neutron Radiography. Radioisotopes **40**, 126–128, 1991a.

NAKANISHI, T. M., MATSUMOTO, S. and KOBAYASHI, H.: Application of Neutron Radiography to the Study of Water Behavior in Soil. Radioisotopes **40**, 182–187, 1991b.

NAKANISHI, T. M., MATSUMOTO, S. and KOBAYASHI, H.: Morphological Change of Plant Root Revealed by Neutron Radiography. Radioisotopes **41**, 640–644, 1992a.

NAKANISHI, T. M., MATSUMOTO, S. and KOBAYASHI, H.: Application of Neutron Radiography to Plant Research. Proc. of The 4th World Conference on Neutron Radiography. May 10–16, San Francisco, pp. 57–64, 1992b.

NAKANISHI, T. M., MATSUMOTO, S. and KOBAYASHI, H.: Water Hydrology by Neutron Radiography when Water Absorb-ing Polymer was Added to the Soil. Radioisotopes **42**, 30–34, 1993.

(Received Oct. 31, 1994)
(Accepted Mar. 10, 1995)

中性子ラジオグラフィによる樹木中の水分分布の測定

中西友子*・渡邊定元**

(* 東京大学農学部，** 東京大学総合研究資料館)

要　旨

中性子ラジオグラフィ法を用いて樹木中の水分分布像を求める試みを行った。供試材は，東京大学農学部田無演習林に植林されていたクロマツ，メタセコイア，ヒノキ，コナラおよびニセアカシアである。供試材は水分の蒸発を防ぐために，測定の4時間前に伐採し，胸高部位から採取した長さ80 cmの丸太を日本原子力研究所東海研究所に運び，実験の直前に厚さ1 cmの円盤を取り試料とした。試料をX線フィルムとガドリニウムのコンバータを内蔵させたカセットに固定し，中性子照射を行った。照射後，X線フィルム像をスキャンニングして供試円盤の中性子ラジオグラフィ像を得た。像の黒化度は水分量に対応し，解像度は約15 μm であった。樹木中の水分は，主に樹木の外側に分布し，年輪と無関係に分布している場合も見られた。心材部の水分量と辺材部の水分量とが殆ど等しい像を示す樹種と辺材部の水分量が心材部のそれより多い像を示す樹種があった。アカシアの場合には，疑年輪や導管が鮮明な像として観察された。本研究は，樹木研究への中性子ラジオグラフィ法の初めての試みであり，更に，手法を改良することにより，樹木中の水分のみならず，組織変化も追跡できるものと予想される。

キーワード：中性子ラジオグラフィ，クロマツ，メタセコイア，ヒノキ，コナラ，ニセアカシア

Water Distribution Inside the Woods by Neutron Radiography

Tomoko M. Nakanishi and Sadamoto Watanabe

Neutron radiography (NRG) was applied to know the water distribution inside the wood, for the first time. Five kinds of woods, *Pinus thunbergii*, *Metasequoia glyptostroboides*, *Chamaecyparis obtusa*, *Quercus serrata* and *Robinia pseudoacacia* were used. The NRG was performed by an atomic reactor at Japan Atomic Energy Research Institute. X-ray film was exposed to the neutrons, after penetrating the sample, to get the image, which resolution was about 15 μm. Water distributing pattern was drastically changed within the samples and was not necessarily along with annual rings. NRG was shown to be a promising method to analyze water movements inside the wood.

Study on the Regeneration Dynamics of Natural Forests in the Chichibu Mountains, Central Japan III

—An artificial disturvance occurred ca. 145 years ago and its effect on the regeneration process of natural Hinoki (*Chamaecyparis obtusa*) stands—

Haruo Sawada, Mikio Kaji, Yuji Igarashi and Kazuya Omura

The disturbance and its effect to the regeneration process of natural Hinoki (*Chamaecyparis obtusa*) stands at Hidana watershed in the Chichibu Mountains, Central Japan were studied by analysing age and diameter growth of canopy trees within the plots and historical facts in Tochimoto village.

The age of the disturbance inferred from the analyses of age composition and growth patterns of canopy trees, well coincides with that of logging found in the history of Tochimoto Village. Therefore, the stands dominated by Hinoki at present were supposed to have been regenerated by the effect of logging occurring 145 years ago (in ca. 1845).