RIKEN Compact Neutron Systems with Fast and Slow Neutrons*)

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(Received 6 August 2017 / Accepted 3 October 2017)

RIKEN has developed accelerator-driven compact pulse neutron systems for practical use in industrial applications and non-destructive infrastructure inspection that are called RIKEN accelerator-driven compact neutron source (RANS) and RANS2. The visualization method for corrosion, the corrosion's related water movement in painted steels, the analytical method for the quantitative estimation of the water movement in painted steels, a neutron engineering diffractometer for texture evaluation, and the austenite volume fraction estimation of iron and steel have been successfully observed through slow neutron applications. For fast neutron imaging applications, a pixel imaging detector for fast neutrons with energy levels above 1 MeV has been developed and used to produce images of a steel bar and an air gap through 30 cm of concrete. The salt concentrations of 4-cm and 5-cm thick mortar blocks have been measured, and a correlation diagram was obtained for a density of up to 1 kg/m^3. RANS2 is now undergoing further development, particularly for outdoor use, as the first test model of an on-site compact neutron system. In this development, RANS2 is equipped with a 2.49-MeV three-fold proton accelerator with an RFQ of 200 MHz.

Keywords: compact neutron source, proton linac, non-destructive testing, infrastructure

DOI: 10.1585/pfr.13.2401017

1. Introduction

Accelerator-driven compact neutron sources have attracted much attention not only in neutron and X-ray fields but also in fields such as materials development aimed at significant weight reduction in automobiles and other transportations, cancer therapy, and non-destructive inspection technology. A neutron beam has unique characteristics such as high penetration power for penetrating into steels and metals and high sensitivity for light elements (e.g., hydrogen, lithium, and boron), thus making the neutron beam an ideal probe for material development. RIKEN has developed an accelerator-driven compact neutron source, RIKEN accelerator-driven compact neutron source (RANS) [1], as shown in Fig. 1, which is easily accessible on-site. There are two major goals of RANS research and development. One is to establish a new compact floor-standing type low-energy neutron system for industrial use. Another goal is to invent a novel transportable compact neutron system for the preventive maintenance of large-scale construction, such as bridges and airports, using a high-energy neutron beam of ∼100 keV. To achieve these goals, a proton linac with a kinetic energy of 7 MeV is used.

Pulsed protons with energies of 7 MeV bombard a beryllium target [2] at the center of the target station and generate neutrons with an energy on the order of MeV via the Be(p,n) reaction.

The neutron energy spectrum that is 5 m away from the target is shown in Fig. 2.

The energy ranges from 1 meV to 5 MeV, which is a difference of nine orders of magnitude in eV. The cen-

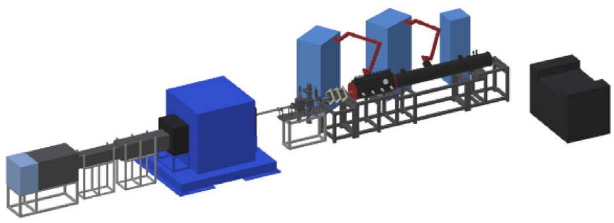

Fig. 1 3D view of the RIKEN accelerator-driven compact neutron source (RANS).

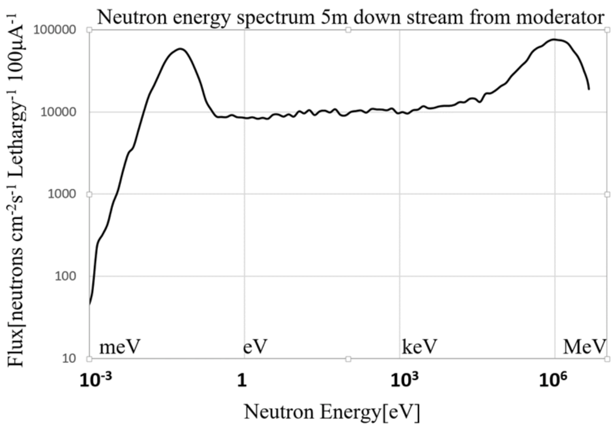

Fig. 2 Neutron energy spectrum 5 m away from the Be target in log-scale.

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*) This article is based on the presentation at the Conference on Laser Energy Science / Laser and Accelerator Neutron Sources and Applications 2017.

tral energy of the left peak is 50 meV, the so-called thermal neutron beam range. Its right peak is at ∼1.5 MeV. The number of neutrons at the sample position is $\sim 10^4\ \mathrm{s}^{-1}$, which is sufficiently low to avoid the production of any radioactive materials during the duration of the measurement.

2. Industrial Applications of RANS

2.1 Corrosion visualization in steel under a film with neutrons using RANS

Corrosion of different types of steel is one of the main issues associated with infrastructure degradation. It is quite difficult to observe the corrosion and its related water movement in steel non-destructively. Neutrons have a high sensitivity to hydrogen and a high penetrative power for steel. We have succeeded in visualizing the corrosion and water movement using RANS [3, 4].

Two steel plates, a regular steel plate (SM400) [5] and a corrosion-resistant alloy steel plate (0.8Cu-0.4Ni-0.05Ti), were prepared through a collaboration with Kobe Steel. Both plates were machined to plates of 6 mm in thickness, 70 mm in width, and 140 mm in height. They were coated with epoxy-modified paint with a thickness of 240 μm and low corrosion resistance. The plates were scratched with a sharp knife to fix the site of corrosion and simulate a film defect. This scratch produces a region much rougher than that in practical environments. The plates were then subjected to a cyclic corrosion test; the salt water spray conditions were 1.5 ± 0.5 ml/h per sample area of 80 cm^2 with 5 wt.% concentration. These steel plates were prepared as samples for water-imaging experiments. Optical images of the samples are shown in Fig. 3 (a). Their neutron transmission images with RANS are shown in Fig. 3 (b). The corrosion in the painted steel is clearly observed as a shadow in the neutron image. This clarifies that neutron imaging is a new tool for the non-destructive observation of corrosion under the paint of painted steel. Corrosion is caused by the presence of water and oxygen; the presence of water is the most important factor. The duration of contact between water and bare steel, i.e., the water detention period in the under-film corrosion of steel, can be considered to have a strong correlation with corrosion. However, there are no studies to prove this relationship. Thus, measuring the water detention period in corrosion is necessary for discussing the corrosion mechanism. The water detention period was successfully observed with RANS neutrons. Before their exposure to neutrons, samples were soaked in distilled water for 2 h. The saturation of the amount of water contained in each sample was confirmed by weight monitoring. After the sample was removed from the water, the surface was wiped to remove the water. Then, the sample was mounted in the enclosure. Figure 4 shows the change in the water distribution of the two samples. Water is primarily distributed in the center of the sample. The regular steel sample has a larger area that contains water than the alloy sample. The water almost disappears after 2 h of drying for the alloy steel sample, but some water remains in the regular steel sample.

The behavior of water in the regular steel sample and the behavior of water in the corrosion-resistant alloy steel sample were compared. The alloy sample contained less water than the regular sample, and the water in the alloy escaped more rapidly than that in the regular sample. Thus, the alloy steel sample had a better corrosion resistance than the regular steel sample.

2.2 Neutron diffractometer using RANS for iron-steel material investigation on-site

Neutron diffraction is known as the only method that can measure the internal strains of crystalline materials non-destructively. This is also a useful technique to quantitatively measure microstructural characteristics of metals, such as microstrain, texture, and dislocation density in the bulk, which are strongly related to its mechanical properties, such as material strength and deformability. Neutron diffraction experiments were performed using RANS for

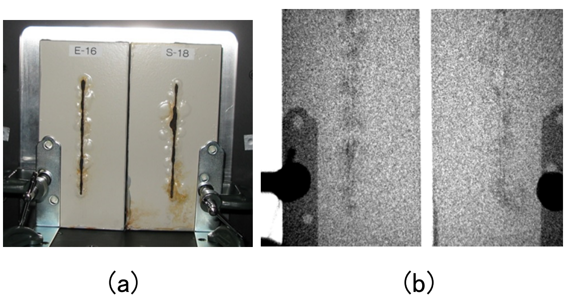

Fig. 3 Visualization of corrosion in different types of steel with neutrons using RANS. (a) Image of samples in front of a neutron camera, including corrosion-resistant alloy steel (left) and regular steel (right). (b) Neutron transmission imaging, in which the central dark shadow is an image of the corrosion in each steel sample.

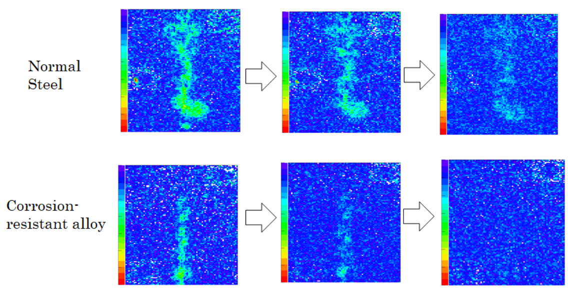

Fig. 4 Visualization of water movement after complete soaking with neutrons using RANS. Nor. stands for "regular steel sample", while All. stands for "corrosion-resistant alloy sample".

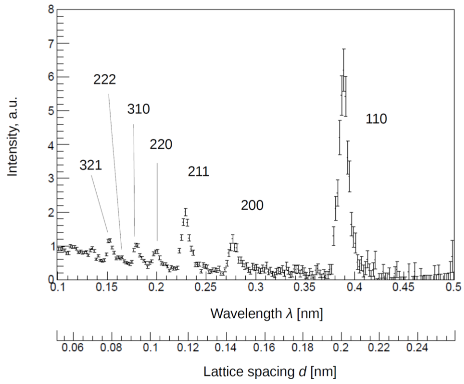

Fig. 5 Diffraction pattern of ferritic steel measured at a diffraction angle of 150°. The diffraction peaks can be identified as a body-centered crystal structure [6].

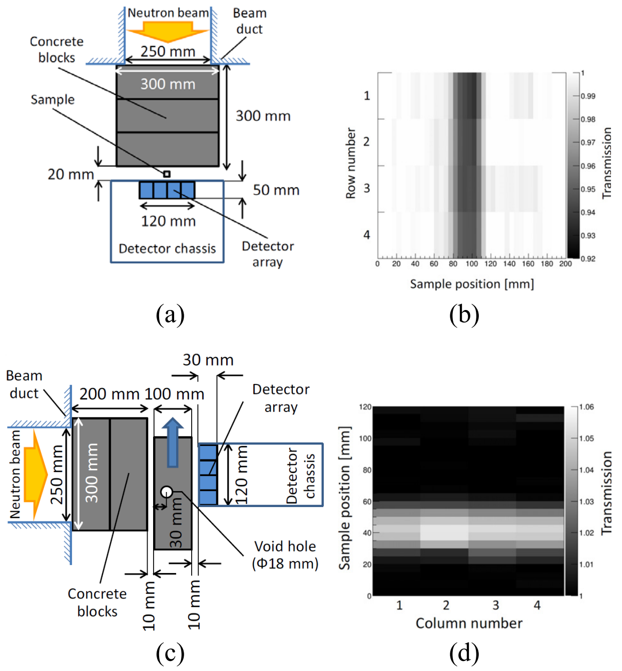

Fig. 6 Fast neutron transmission imaging of iron rods and void holes in concrete. (a) Experimental setup. Fast neutrons entered the 300-mm thick concrete slabs with iron rods placed behind them. The fast neutron imaging detector, which had a length of 120 mm, was placed at the back. (b) Transmission imaging of the iron rod shadow acquired by the detector. (c) Experimental setup. (d) Imaging of the hole [8].

determining the capability of the compact neutron source for neutron engineering diffraction and for aiming for easy access measurement of the texture and the amount of retained austenite [6]. Figure 5 shows the diffraction pattern of a ferritic steel specimen, taken for 10 min, given as a function of wavelength. This diffraction pattern was calibrated by time-focusing to the center of the detector.

The texture evolution caused by plastic deformation was successfully observed by measuring a change in the diffraction peak intensity, and the volume fraction of the austenitic phase in the dual-phase mock specimen was also successfully evaluated by fitting the diffraction pattern with Rietveld analysis within 2% accuracy, as shown in [6].

3. Fast Neutron Non-Destructive Observation Technique

The deterioration of transportation infrastructure is a major but common problem around the world. There are 720,000 bridges in Japan. From 2014, they have been examined every five years. However, no technique has been proposed to observe the inside of a concrete slab or to find corrosion in the joints of large steel bridges to accurately assess or diagnose which bridges urgently need maintenance and when this maintenance should be done. We propose a new imaging technique for bulk concrete structures that uses fast neutrons with energies greater than 1 MeV emanating from RANS. This technique has been developed considering the characteristics above 1 MeV neutrons, which can penetrate concrete slabs at a depth of more than 30 cm [8].

Fast neutrons transmitted through 30-cm thick concrete with a hole 18 mm in diameter were measured, as shown in Fig. 6 (a). The position of the hole was observed as an air void, as shown in Fig. 6 (b).

The large transmission probability of fast neutrons, indicated by lighter colors, was measured at the position of the air hole. This is because the total thickness of the concrete decreases if air holes exist.

When the experiment was performed, the sample and the detector were set 5 m away from the target because of the limit set by radiation regulations at the place where the experiment was performed. Since RANS has been updated, it is now possible to set the samples 1.5 m away from the target.

Based on these visualization methods, fast neutrons have been known to be good probes to visualize the inside of thick concrete slabs.

Because it is known that the deterioration of a concrete slab can be due to the negative influence of water, "Waterproof layer of reinforced concrete slab on road bridge: Design and construction (1987)" [7] first specified the full-scale provision of waterproofing for slabs. A novel method of backscattering (reflection) neutron imaging method to detect water and voids in concrete has been developed with RANS for its application to non-destructive inspection to determine the deterioration situation, such as resident water and voids in concrete slabs under asphalt pavement surfaces from the road surface side [9]. Two-dimensional imaging of water or voids can be obtained with time-of-flight experiments.

Table 1 Specifications for RANS and RANS2.

	RANS	RANS2
Particle	Proton	Proton
Energy	7 MeV	2.49 MeV
Ion current	100 μA	100 μA
Reaction	9Be(p,n)9B	7Li(p,n)7Be
Accelerator	RFQ + DTL	RFQ
Weight (Accelerator)	5 t	2.5 t
Weight (Target & Shield)	25 t	<1 t (estimation)
Length	15 m	<5 m
Neutron yield	10^{12} neutrons/sec	10^{11} neutrons/sec

4. RANS2 Development

With respect to the radiation level and the amount of shielding for a transportable compact neutron system for on-site use, a small system is appropriate and feasible to use. The neutron yield around a Be target is estimated to be $\sim 10^{12}$ neutrons/s with a current of 100 μA. The small compact neutron source was designed with a low-energy proton beam to make the shielding much smaller than RANS by avoiding fast neutrons with energies greater than 1 MeV. According to the Japanese radiation regulations, an ion beam accelerator whose energy is lower than 2.5 MeV can be operated without designating a radiation-controlled area, except for deuteron beams or the insertion of a neutron-generating target material such as Be or Li, thus avoiding a high gamma ray dose.

RANS2 is being developed and is equipped with a 2.49-MeV three-fold proton accelerator and Li target as the first test model of an on-site compact neutron system, particularly for outdoor use [10]. The specifications of RANS and RANS2 are shown in Table 1. The weights of the accelerator and the target station of RANS are 5 and 25 t, respectively. Based on the experimental results at the RANS facility, the energy of the new accelerator was set at 2.49 MeV. To increase the neutron yield at a low acceleration energy, we chose Li as a target instead of Be. The total weight of RANS2 is estimated to be less than one-fifth of that of RANS because of the massively decreased weight of the shielding. The total neutron yield at a proton current of 100 μA is calculated to be $\sim 10^{11}$ neutrons/s. Although this is only one-tenth of that of RANS, there are many advantages for imaging and other applications. The small shielding system enables all samples to be set closer to the target. For example, a target-sample distance of 1 m yields 25 times more neutrons than that with a target-sample distance of 5 m in the RANS case, 2.5 times more neutrons in RANS2 than in RANS.

5. Conclusion

RANS has proved that it is a comprehensive tool not only for neutron imaging but also for neutron diffraction with iron and steel texture and microscopic characterization studies; in addition, the use of fast neutron imaging for bulk concrete slabs as a new application of non-destructive infrastructure testing has been demonstrated.

The important aspects of the research and the development of a compact neutron source should be based on a combination of source development and analytical technology as a response to requests from users, such as those involved in industrial applications or social safety.

Acknowledgments

This work was partially supported by the Council for Science, Technology and Innovation (CSTI), the Cross-Ministerial Strategic Innovation Promotion Program (SIP), “Infrastructure Maintenance, Renovation and Management” (funding agency: JST), and the Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sport, Science, and Technology, Japan. It was also supported by JSPS KAKENHI, Grant Numbers 25289265 and 25420078. The authors would like to thank the Iron and Steel Institute of Japan (ISIJ) Research Group for their beneficial assistance. The authors would like to thank Enago (www.enago.jp) for the English language review.

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