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THEORETICAL AND PRACTICAL USEFULNESS OF RADIATION METHODS FOR WOOD DENSITY TESTING[1]

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SYNOPSIS. Three pine trunks and three spruce trunks and a lime icon support were tested with application of two radiation methods with the ^{241}Am isotope: the absorption method and the backscatter method, i.e., the method based on the Compton phenomenon with the gamma radiation backscattering. The outcome was as follows: compliance of the radiation measurement as compared against the classic stereometry method, and no impact of the anatomic direction and the wood moisture content on this compliance of results obtained by different methods. The radiation method is useful for detecting differences in density for wood with insects damages, fungi infection or internal fissures.

KEY WORDS: radiation, gamma-defectoscopy, ^{241}Am isotope, density, pine/spruce wood, lime icon support

INTRODUCTION

Method and conditions of structural timbers were established (EN 338:1995, EN 384:1999, PN-82/D-94021). Several strength grading machines, based on non-destructive measurements, used gamma radiation in order to determine density. Systematic investigations were laid down to establish the method and main conditions of this test.

The test results intercede for a valuation of both radiation methods: the absorption method and the gamma radiation backscattering method – both methods are very important for wood science and diagnostics, for practical application.

The wood density is the basic material physical property and that is why the density test accompanies all the other test types. Due to its strict relation to the

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material structure, density is a good indicator of wood mechanical properties, e.g. compressive strength, and of numerous technological properties such as hardness and abrasion resistance. While selecting and applying the structural material, the material density has a significant role beside of the strength, whereas the density is the decisive factor for so-called wood strength quality coefficient (Krzysik 1974).

The wood density test methods are divided as follows: destructive tests – that require samples to be taken from the material for determining the density, and non-destructive tests – that are applied to full-size elements with no need to collect samples. The first group includes the stereometry wood density test, whereas the second group includes: radiation methods, ultrasonic methods, microwave methods, and methods with application of dynamic hardness testers (Dzbeński 1984, Korzeniowski and Dzbeński 1994).

As the need grew for metering the whole batches of wood materials, the need rose as well for a complete parameter control, with density included. This is the case e.g. while stress grading of structural timber for construction industry. As important is also the non-destructive wood density testing capability for wood inbuilt in a structure, for cases such as renovation and repairs of antique wood structures. Such requirements can only be met based on non-destructive tests, with radiology tests in most cases.

Compliant with the European standards (EN 384), strength requirements for structural timber have been additionally complemented with the guarantee density criterion; until that time, the annul rings criterion was estimated the satisfactory indicator of timber technical condition (PN-82/D-93021, BS 4978, ECE Standards). This has been found insufficient in the light of modern wood engineering (Dzbeński 1994, 1995). The EN 338 has introduced twelve strength classes for coniferous timber (C14 . . . C40), and six strength classes for deciduous timber (D30 . . . D70). If qualified to a specific class based on the guaranteed strength and elasticity, timber must meet the minimum density criterion as defined for that class.

With the introduction of European Standards, structural timber featuring strength as guaranteed and the density as required, should be the only type available in the wood market. Manufacturers will be forced not only to get knowledge about the strength-sorting, they will also have to select a useful method – that means: useful for industrial conditions – density measuring method to be applied in a sawmill.

This work has been commenced in order to prove the usability of radiation methods with application of isotopes for non-destructive wood density tests.

The application of low-energy ^{241}Am isotope provides a higher safety of usage, and a higher test selectivity compared to 137Cs that is applied for tests till now, as well as to many other isotopes (Dzbeński 1978).

The tests were made on pine wood (*Pinus sylvestris* L.) and spruce wood (*Picea abies* Karst.) as the raw material most frequently used for manufacturing structural timber in this part of Europe.

MATERIALS AND METHODS

The densitometer for the test was constructed in co-operation of the Faculty of Wood Technology, Szkoła Główna Gospodarstwa Wiejskiego (Warsaw University of Life Sciences), with the Faculty of Physics and Nuclear Technology, Akademia Górniczo-Hutnicza (University of Mining and Metallurgy in Kraków) (Stęgowski and Furman 1995).

The device was applied e.g. by Krzosek (1998) for local wood density tests by absorption method. In this method, the wood density is calculated based on the radiation beam attenuation by the sample tested. The source radiation after attenuation by a board made on the tested wood, was recorded by the SSU-70 scintillation method. Apparatus, after Mańkowski et al. (2004) based on that data, a custom software calculated the material density.

The source (^{241}Am) emits a radiation beam that is attenuated by the sample under test. The comparison of the source radiation beam and of that attenuated by the sample, allows the sample density to be determined.

Figure 1 shows the densitometer for the absorption method wood density test.

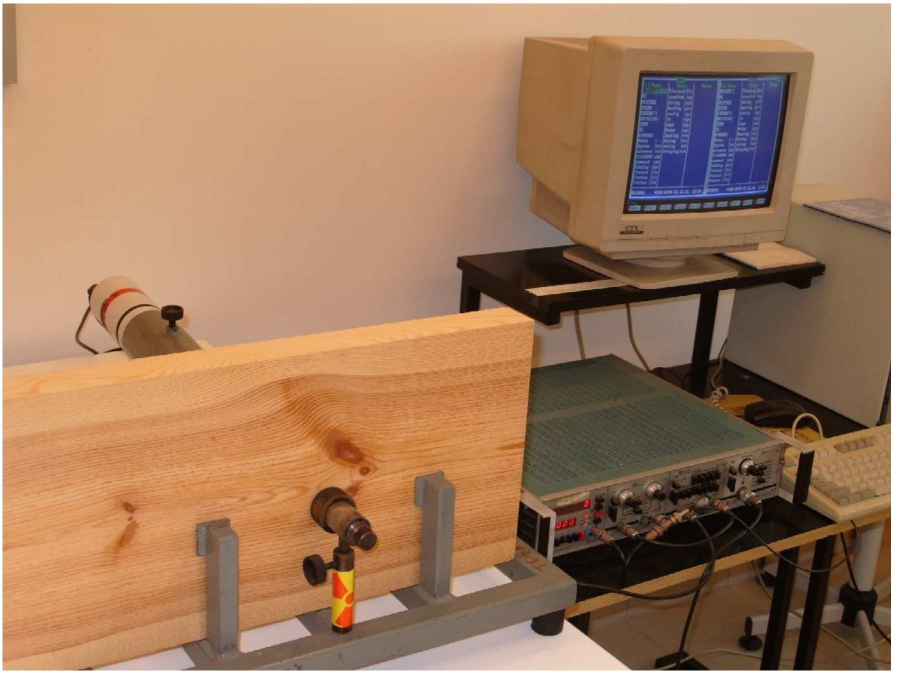

Fig. 1. Densitometer for absorption method wood density test

The radiation beam is strongly collimated just after the source and in additional location at the probe inlet. This collimator configuration determines the sample volume that impacts the test result. A selected beam collimation allows different "locality" grade for the test.

In the absorption method, the density is calculated from the following formula:

$$\rho_p = \frac{1}{\mu \cdot g_p} \cdot \ln\left(\frac{I_o - I_t}{I_p - I_t}\right) \tag{1}$$

whereas: ρ_p – density by absorption (attenuation) method [kg/m^3],
g_p – sample thickness [mm],
I_o – source radiation rate [pulses/sec],
I_p – radiation rate after sample [pulses/sec],
I_t – background radiation rate [pulses/sec],
μ – mass absorption (attenuation)coefficient [–].

After a redesign, the densitometer is capable of operating with application of the Compton phenomenon. The backscattering method (that requires no access to the wood from the other side) makes this method applicable for density tests in restricted-access locations, such as wood in-built in existing structures, or wood stored in staples/stacks.

In the further text, the method that applies the Compton phenomenon will be called the backscatter method to mate it easier. The densitometer was adapted to that method by changing positions of both the source and the detector as well as by updating the calculation software. Additionally, a lead absorbent was located between the probe and the source for protecting the counter from direct radiation. This way, all probe records include gamma photons back-scattered by the wood sample, and the natural background.

The operation principle for an isotope densitometer operating by backscatter method was described below. The source (^{241}Am) emits a radiation beam that goes through the sample under test. A part of the radiation is backscattered on the material tested, and a part of that backscattered radiation is sensed by the probe.

The comparison of the source radiation against the radiation backscattered on the sample, allows the density to be calculated.

The densitometer for the backscatter method density test is shown in Figure 2. In this method, the result does depend on the test geometry. After any change of the test configuration, test devices should be calibrated again.

The software calculated the wood density with account for its thickness, moisture content and other physical parameters related to the test (source radiation rate, background radiation rate, calibration against the reference). While developing the software, outcomes of theoretical and experimental works of Muchorowska and Gierlik (1997) were taken into account. It resulted from those works that the backscattered radiation rate was proportional to the density of wood or of a plastic material built from elements similar to that of wood. Plastic is recommended as references due to their uniform structure and dimensional stability.

The amount of radiation backscattered from the sample is compared against the radiation backscattered from the reference of a known thickness and density. The sample density can be calculated based on those data.

The formula for calculating the density (determined from measurements) is as follows:

$$\rho_c = \frac{I_p - I_t}{I_{wz} - I_t} \cdot \frac{g_{wz}}{g_p} \rho_{wz} \tag{2}$$

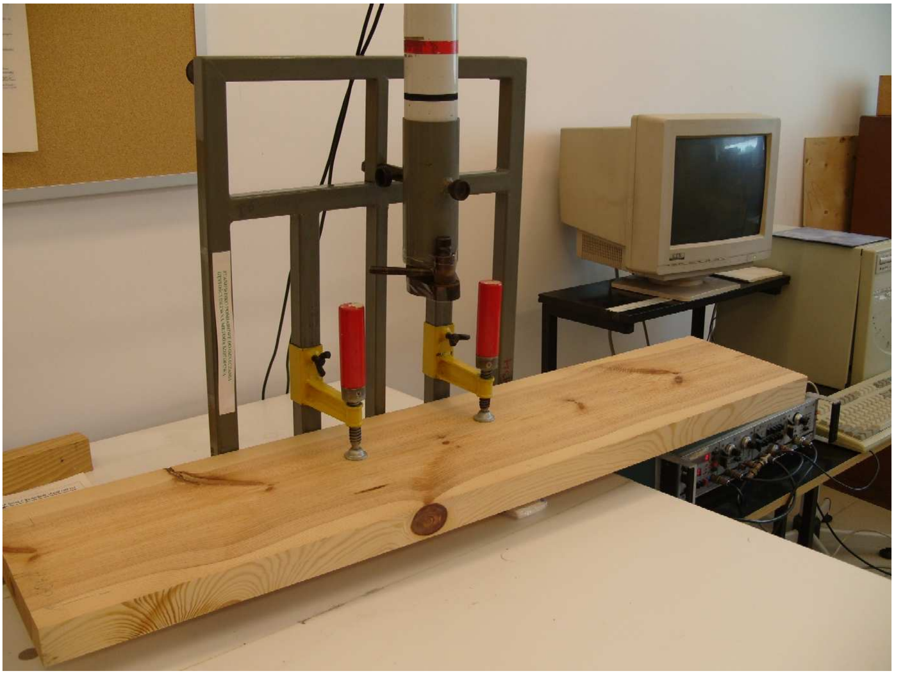

Fig. 2. Densitometer for the backscatter density test

whereas: ρ_c – density calculated by absorption (attenuation) method [kg/m^3],
ρ_{wz} – reference sample density [kg/m^3],
I_{wz} – sample-backscattered radiation rate [pulses/sec],
I_p – reference-backscattered radiation rate [pulses/sec],
I_t – background radiation (attenuation) rate [pulses/sec],
g_{wz} – reference thickness [mm],
g_p – sample thickness [mm].

The densitometer was so set-up that the test result be equal to the average density for a roll of 50 mm diameter.

Before every test series, the devices were calibrated on the reference sample. As the reference sample, Plexiglas was used because it had the same thickness as that of the wood to be tested. The Plexiglas structure is uniform, and its density is known ($\rho_{wz} = 1050$ kg/m^3). Its elementary composition is similar to that of wood that results in the mass absorption coefficients of both materials being the same in practice.

Based on the data existing in the literature, GIERLIK and DZBEŃSKI (1996) studied the influence of moisure content on the mass absorption (attenuation) coefficient for four levels of moisure content of wood, namely 0, 9.5, 18.5 and 26.8%. A nonsignificant relationship was obtained.

RESULTS AND DISCUSSION

Wood density by absorption method

The density of defect-free 5 × 5 × 22 cm pine wood samples was tested with the densitometer applied. The tests were made for different moisture content levels (0%, 5%, 15%, 28%, and 70%). On each sample, tests were made for 15 points distributed uniformly in the radial direction. The density of those samples was also tested by stereometry method. The comparison of results is shown in Table 1.

Table 1. Density by isotope method and by stereometry method for pine samples, 5 × 5 × 22 cm, no visible defects, for different moisture content levels

Method of density control	Moisture content [%]					
	0	5	10	15	28	70
Stereometric	[kg/m^3]					
Medium density	523	608	608	618	634	703
Isotope	[kg/m^3]					
Medium density	526	601	610	610	628	694
Min value of density	482	573	572	585	572	606
Max value of density	574	645	630	649	679	732
Diference: max. − min	92	72	58	64	107	126

It was found in the outcome that for each humidity level, the average density as calculated based on 15 tests made by the isotope method was almost identical to that of the same samples as calculated by the stereometry method.

Within the same tests, isotope tests were made for the impact of anatomic direction on the density. Twenty samples were taken by chance (both from sapwood, and heartwood) from each wood species. For each sample, three density tests were made in the tangential direction, and three in the radial direction, and then average data were calculated for both directions.

The distribution of wood density on radial and tangential directions are given in Figures 3 and 4.

The correlation coefficients: r = 0.883 for pine wood, r = 0.892 for spruce wood, are very high and prove a very strong relation between the density tested in the radial direction and in tangential direction. It results from the tests, that the impact of anatomic direction on the sensitivity parameter by isotope methods, lowers with the increased number of tests.

In the next test series, density was tested for spruce trunks and pine trunks over the entire length from the buttress up to the top. The tests were made on 50 mm timber samples made from trunks after dividing in logs, and then in samples. Tests were made for two average balks from the trunk interior part, for sapwood and for heartwood separately, two series of tests for each. So, four tests for heartwood density, and four tests for sapwood density were made on each cross-section. The data collected that way for wood density distribution from the buttress up to the top, are shown after averaging as curves in Figures 5, 6, for sapwood and for heartwood separately.

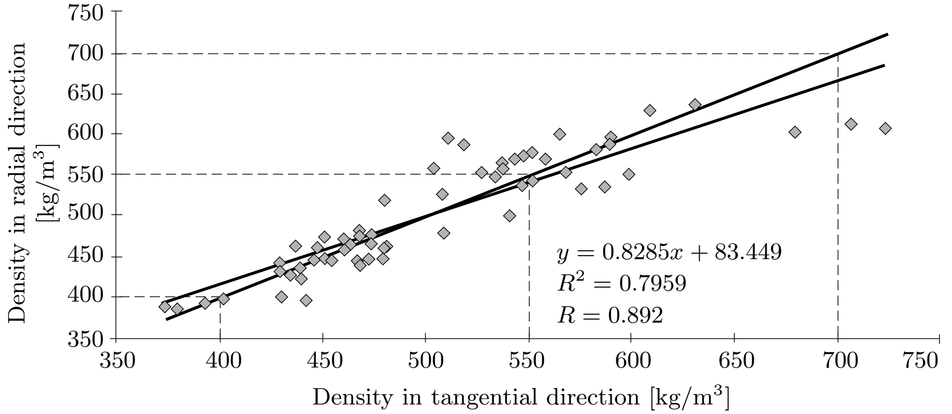

Fig. 3. Relation between density test result for pine wood in radial direction and tangential direction

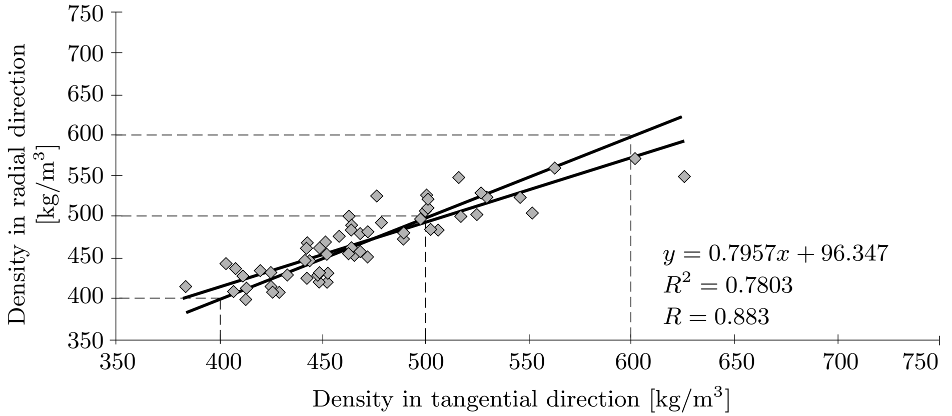

Fig. 4. Relation between density test result for spruce wood in radial direction and tangential direction

The result allows to make the statement (in compliance with observation of researchers who applied the stereometry density test: TRENDELENBURG (1955), KRZYSIK (1974)) that the pine wood density decreases from the buttress to the top.

Wood density test by backscattering method over the trunk length

The backscattering method for the wood density test is easily applied e.g. for testing raw material. Figures 7, 8 show an example of density curve for spruce sapwood and heartwood over the trunk height (length).

The distance between test points was as small as 50 mm. The application of such a short step allows for a stepless test in practice.

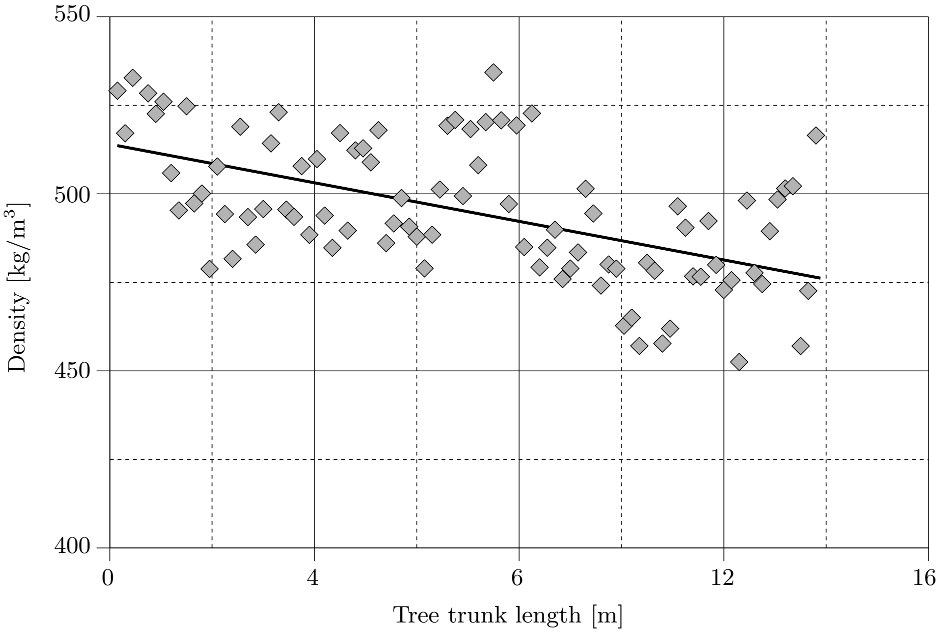

Fig. 5. Wood density distribution for pine sapwood over the stem height

Fig. 6. Wood density distribution for pine heartwood over the stem height

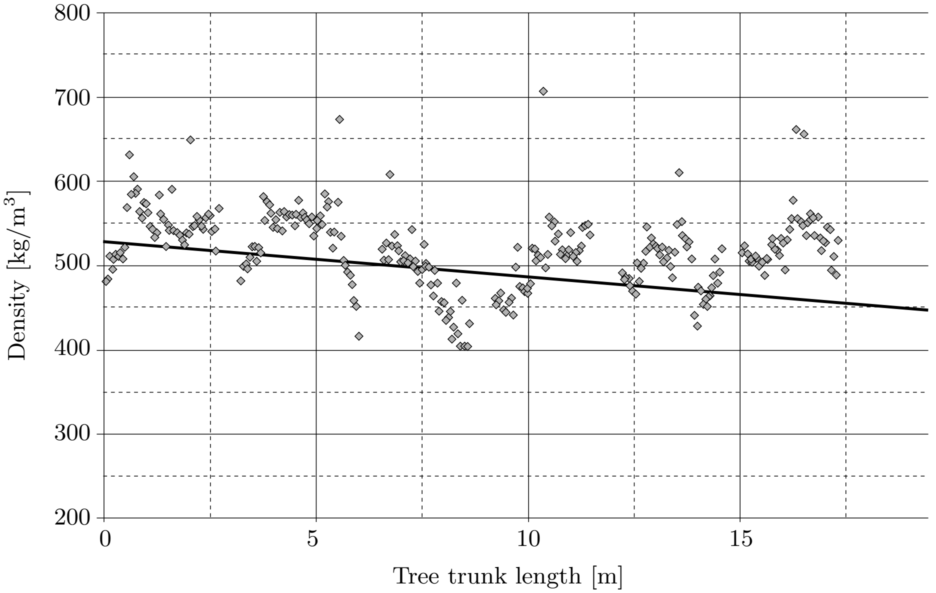

Fig. 7. Spruce sapwood density distribution over the stem height

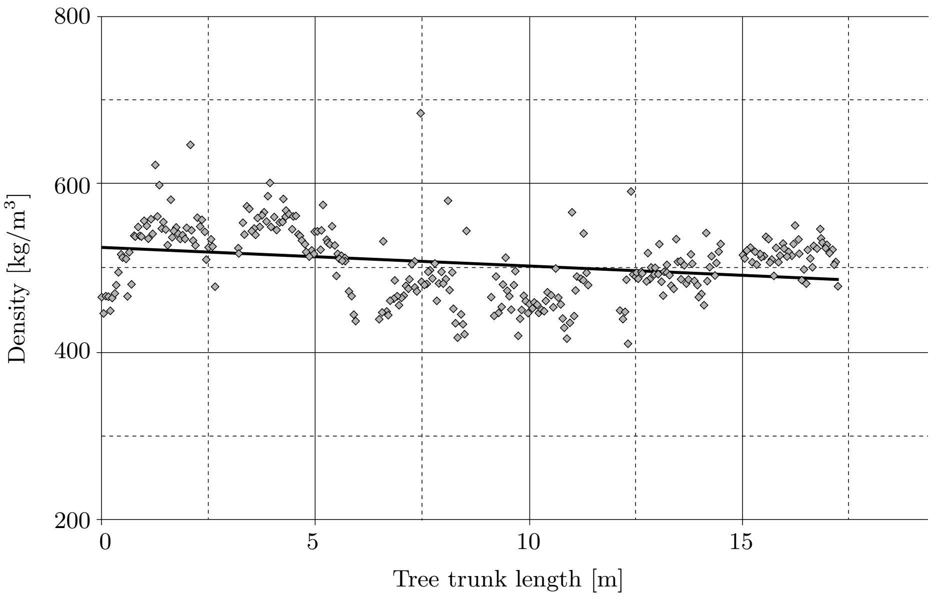

Fig. 8. Spruce heartwood density distribution over the stem height

It results from the data collected that the density difference can amount up to 50 kg/m^3 for test points spaced by as little as 50 mm. This means the possibility of significant density differences in a seemingly uniform (no visible defects) test material. Due to that significant variation, the assumption for so-called "check samples" must be considered with carefulness. Uncritically applying such samples can be the reason for significant errors.

The density parameters for spruce heartwood as shown in Figure 8, have a slight decreasing trend in the direction from the buttress to the top. As well, just an insignificant decrease trend is shown for the spruce sapwood density (Fig. 7). Such a phenomenon that is non-typical to other wood species, was recorded many years ago by Trendelenburg (1955) in stereometric tests.

Results that significantly differ from the average, come from the area around knots as test points were in many cases located on a knot or in its direct neighbourhood. The average density for a knotless spruce heartwood was 505 kg/m^3 while the maximum within a knot amounted to 684 kg/m^3.

The application of gamma rays method in the wood industry is very limited because of the high cost of the device. Isotopical scanners (for ionizing radiation) have been used for laboratory tests performed for drying control of lumber and for detection of voids in wood-based composites. Gamma ray scanning densitometry has been more frequently used for the measurement of the densitometric profile of tree trunk.

Investigation of lime icon support

As proven before, radiation methods find a significant practical application in testing the wood density for both living tree trunks. It is evident that the radiation method can be useful for stress grading of timber for structural use and for diagnostics of old wooden architectures relic and other wooden remnants (sculptures, pictures, picture frames).

The radiation technology proves very useful for detecting wood density differences caused by insects, fungi infection or other reasons (e.g. internal fissures).

Research was made at the SGGW (Division of Wood Science (Mańkowski et al. 2002)) by the radiation backscattering method with an isotope densitimeter Am-241 (370 MBq activity). The radiation was diffused back by the lime wood board used as a support for Saint Nicholas icon (dimensions 25 × 388 × 345 mm) tested. The density of the remnants can be calculated based on the object thickness, pattern sample thickness (a board from contemporary lime wood:32 mm thickness, 442 kg/m^3 density) and on the amount of backscattering radiation.

Based on the distribution of lower density zones that resulted from the insects-caused damage (hole) conclusions can be drawn on the destruction extent caused by Woodworms (*Anobium punctatum*) on the painted side (Fig. 9a) and on the support reverse side (Fig. 9b). The wood support density on the painted side is higher compared to the one on the support reverse side, this related probably to the use of silver and different pigments for painting the icon. Two horizontal zones of a significantly higher density are related in vertical cross-bars (crosswise

Fig. 9a. Density distribution map on the painted side

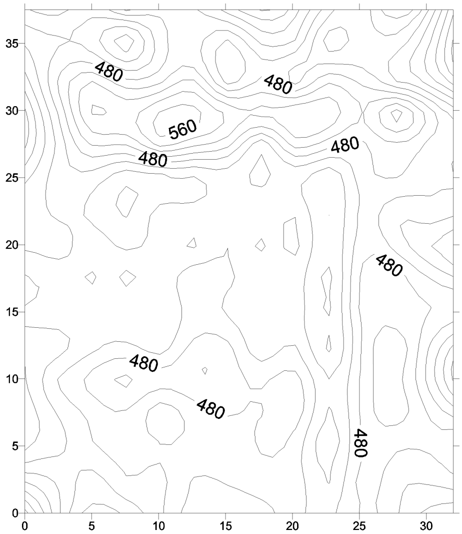

Fig. 9b. Density distribution map on the support reverse side

reinforcement made from coniferous wood a higher density). A vertical zone featuring a lower density coincides with the location of the surface fissure between two boards of the lime support.

CONCLUSIONS

1. Both radiation methods: the absorption method, and the ^{241}Am gamma radiation backscattering method, are equally useful for density tests for coniferous round wood and timber.
2. The results from the radiation method density tests, do not depend on the anatomic direction (radial or tangential) in wood.
3. The results from the non-destructive radiation method show a satisfactory compliance to those obtained from the classis stereometric method, but are obtained much quicker, do not require taking samples and destroying the object under test.
4. The radiation method is useful for detecting differences of density for wood with insects damage, fungi infection or internal fissures.

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