

## GAMMA-RAY ATTENUATION TECHNIQUE FOR DETERMINING DENSITY AND WATER CONTENT OF WOOD SAMPLES

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**ABSTRACT** - The method of determination of density and moisture content in wood samples by attenuation of a collimated monoenergetic beam of Am gamma-radiation is presented as the recommended method for flow studies in wood for being indestructible, fast and with good sensitivity. The theoretical aspects of the application of the Beer-Lambert law are discussed, with emphasis on the maximum theoretical error expected. A series of measurements of moisture content within the range of 8 g/cm<sup>3</sup> to 30 g/cm<sup>3</sup> are made on samples of **Pinus oocarpa** by gamma-ray attenuation methods and by the conventional gravimetric method. The relative deviations (experimental errors) found in the determinations made by these two methods are compared with the theoretical errors calculated, showing the viability of the gamma-ray method.

**RESUMO** - O método de determinação de densidade e de umidade em amostras de madeira por atenuação de um feixe colimado e monoenergético de radiação gama do <sup>241</sup>Am é apresentado e recomendado para estudos estáticos e dinâmicos de fluídos em amostras de madeira, com as vantagens de ser indestrutível, rápido e com boa sensibilidade. Os aspectos teóricos de aplicação da Lei de Beer-Lambert são discutidos, dando-se ênfase ao máximo erro teórico esperado. Uma série de medidas de umidade, na faixa de 8 g/cm<sup>3</sup> a 30 g/cm<sup>3</sup>, foi realizada em amostras de **Pinus oocarpa**, pelos métodos de radiação gama e gravimétrico convencional. Os desvios relativos (erros experimentais) encontrados, foram comparados com o erro teórico calculado, e mostraram a viabilidade do método gama.

### INTRODUCTION

The method of determination of wood density and moisture content by gamma-ray attenuation technique was recommended by some investigators in the 1950's and subsequently presented by LOOS in 1961. PARRISH (1961) soon set about perfecting the method with the use of non-conventional gamma radiation energy. Next came the works of LOOS (1965), WOODS (1965) and PHILLIOS (1965) which are the most significant.

Most of these authors used as gamma ray source the <sup>137</sup>Cs, the photo peak which has an energy of 662 KeV. Due to the low density of the material (wood) and the low values of its mass attenuation coefficient, the interaction of photons of this energy band is not sufficient to provide good sensitivity, even for large samples. In most cases, samples around 50 cm in thickness are needed in order to achieve good Interaction between

radiation and the matter. As usually 3 to 8 cm thick wood samples are used, the sensitivity of the method is very low when  $^{137}\text{Cs}$  is used.

FERRAZ (1976) introduced the use of  $^{241}\text{Am}$  as gamma-ray source due to its low energy, which is 60 KeV. With this the method came into use again, mainly for water-flow measurements in wood, due to its good sensitivity, simplicity and indestructibility.

In the present paper the theory of the method is discussed, as well as the limits for its application and the theoretical and experimental errors in the measurements.

### Theory

A wood sample can be considered as being constituted by 3 distinct substances: wood itself, water and air. The apparent density ( $d_m$ ) of the sample is defined (KOLLMANN and COTE Jr., 1968) as being the ratio between dry matter and total volume of the system (wood + water + air) for given moisture content:

$$d_m = \frac{m_s}{V_u} \quad (1)$$

The moisture content (U) of a sample is defined by the percentage of dry matter in the total mass (wood + water + air) (SKAAR, 1972):

$$U = \frac{m - m_s}{m} \cdot 100 \quad (2)$$

When a gamma-radiation beam with initial intensity  $I_0$  passes through this sample, it is attenuated by a fraction I, ( $I - I - I$ ), as a result of the interaction between radiation and wood, water and air portions. For this particular case, the Beer Lambert's law can be written as follows:

$$I = I_0 \exp - [\mu_m \rho_m \theta_m x + \mu_w \rho_w \theta_w + \mu_a \rho_a x (\theta_a - 1)] \quad (3)$$

Where

$\mu_m, \mu_w, \mu_a$  = mass attenuation coefficients for wood, water and air ( $\text{cm}^2/\text{g}$ )

$\rho_m, \rho_w, \rho_a$  = wood, water, air substance densities ( $\text{g}/\text{cm}^3$ )

$\theta_m, \theta_w, \theta_a$  = wood, water, air volumetric fractions:

$$\theta_m = \frac{V_m}{V_u}$$

$$\theta_w = \frac{V_w}{V_u}$$

$$\theta_a = \frac{V_a}{V_u}$$

x = sample thickness (cm)

Under normal conditions of temperature and atmospheric pressure,  $\rho_a = 1.2 \times 10^{-3} \text{ g/m}^{-3}$  and  $\rho_w = 1.0 \text{ g.cm}^{-3}$ . Thus, the last portion within the exponential which refers to the attenuation by the air layer, can be neglected, for it represents values that are  $10^3$  to  $10^4$  smaller. Thus equation (3) can be written in the following simplified manner:

$$I = I_0 \exp - [x([\mu_m \rho_m \theta_u + \mu_w \theta_w \rho_w]) \quad (4)$$

As  $\theta_m = d_m/P_m$  and as for moisture content values below the fiber saturation point, i.e., when there is no free water in the system.

$$\theta_w = \frac{U}{100} \cdot \frac{d_m}{d_a} \quad (5)$$

(4) can be written as

$$I = I_0 \exp - [x(\mu_m d_m + \mu_w \frac{U}{100} \frac{d_m}{d} \rho_w)] \quad (6)$$

$$dm = \frac{\ln(I_0/I)}{x(\frac{U\mu_w\rho_w}{100d_a} + \mu_m)} \quad (7)$$

$$U = [\frac{\ln(I_0/I)}{x d_m} - \mu_m] \frac{100d_a}{\mu_w \rho_w} \quad (8)$$

Equation (6), and consequently equations (7) and (8), contains three unknown quantities, which are: wood density ( $d_m$ ), moisture content (U) and density of the water absorbed in cell walls ( $d_a$ ).  $d_a$  is a function of moisture content ( $d_a = f(U)$ ) and can be estimated through experimental relations (AGUIAR et al., 1980). Thus, two unknown

quantities are left, wood density and moisture content, and to determine any them, the previous knowledge of the other is necessary.

### Errors in the Determination of Moisture Content

The theoretical error in the determination of moisture content (or density) can be obtained through the partial derivations of the function described (8), once the maximum absolute errors in the measurements are known (AGUIAR, 1980).

FERRAZ and MANSELL (1979), studying the errors in the determination of soil density and moisture content by gamma-ray attenuation technique, point out that the exactness of the method is limited mainly by errors made in the determinations of  $I_0$  and  $I$ , as a consequence of random radioactive disintegration. Thus, under ideal conditions for measurement, i.e., when the errors made in the measurement of the other parameters ( $x$ ,  $d_m$ ,  $d_a$ ,  $\mu_m$  and  $\mu_w$ ) are negligible, it can be said that the errors in the measurements of  $U$  are those from measurements of  $\ln(I_0/I)$ .

By differentiating the fundamental equation (6) as to moisture content the following is obtained:

$$\frac{dI}{dU} = -I \times \frac{\mu_w d_m}{100d_a} \cdot \rho_w \quad (9)$$

According to WAN et al. (1975), the relative error in the measurement of  $I$  can be considered as being equal to  $1/\sqrt{I}$ :

$$\frac{dI}{I} = \frac{1}{\sqrt{I}} \quad (10)$$

Substituting (10) in (9), it comes to

$$\frac{1}{I} = - \frac{\mu_w d_m \rho_w}{100 d_a} \cdot dU \quad (11)$$

Replacing  $I$  with its value in equation (6), expressions for relative and absolute errors in moisture measurements can be obtained:

$$|dU| = \frac{100d_a}{x d_m u_w \sqrt{I_0 P_w}} \exp\left[\frac{x d_m}{2} \left(\mu_m + \frac{U \mu_w \rho_w}{100 d_a}\right)\right] \quad (12)$$

$$|\delta U| = \frac{100d_a}{x d_m u_w \sqrt{I_0 P_w}} \exp\left[\frac{x d_m}{2} \left(\mu_m + \frac{U \mu_w \rho_w}{100 d_a}\right)\right] \quad (13)$$

## Experimental Part

In order to know the precision of the gamma-ray attenuation method for determination of moisture content in wood, an experiment was planned with 5 **Pinus oocarpa** samples from an 18-year old tree, each sample being 4 x 6 x 13 cm. The samples were conditioned in an environment with controlled relative humidity and temperature until they reached moisture content between 9% and 30% (as defined in relation 2). As the time needed for the samples to reach moisture content in equilibrium with the environment was variable, it was stipulated that a state of equilibrium would be achieved when the mass remained unaltered after three successive weightings.

Once this point of equilibrium was reached, the sample was taken to the gamma-ray system for counting. In order to avoid the heterogeneity of the sample, 25 determinations were made at different points on a counting rate higher than 100,000 cpm.

An ORTEC single-channel gamma spectrometer was used, with a 2" x 1/4" scintillation detector, coupled to a Harshaw photomultiplier. The leaden collimator, on both the detector side and the source side, measured 20 mm in length and 4mm in cross section diameter. The distance between the two collimators was 120 mm. A <sup>241</sup>Am gamma-ray source was used, of approximately 100 mCi, which provided an absorption-free photon flux of the order of 210,000 cpm.

The mass attenuation coefficients of wood and water were previously determined:

$$\mu_m = 0.1855 \pm 0.0005 \text{ (cm}^2\text{/g)}$$

$$\mu_w = 0.2034 \pm 0.0003 \text{ (cm}^2\text{/g)}$$

For the U calculations, corrections were made for the dead-time counting and for density of adsorbed water (AGUIAR et al., 1980). The weightings were made on a Mettler balance (P 163) with 0.001 g precision, the samples were measured with a Mitutoyo caliper with 0.002 cm precision. The calculations were made with a HP 8910 calculator, with a program developed by AGUIAR (1980).

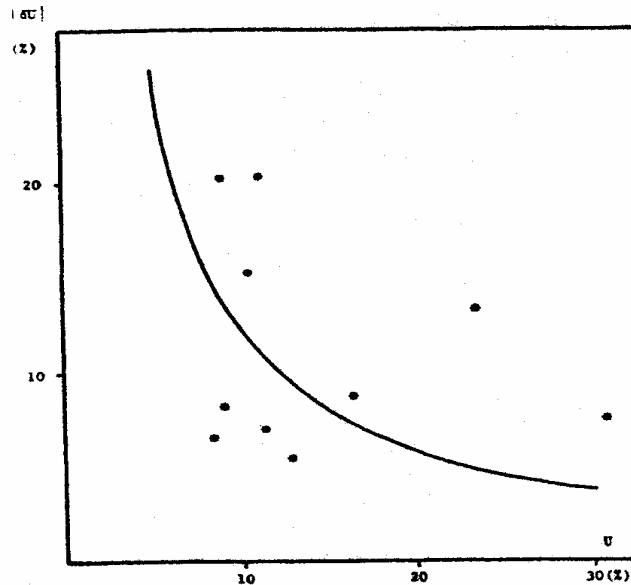
## RESULTS AND DISCUSSION

To evaluate the gamma methodology, a comparison was made between the moisture content calculated according to relation (8), which was conventionally called U, and the moisture content calculated by the traditional gravimetric method, according to relation (2), which was called U<sub>g</sub>. The values obtained through the two methods are shown in Table I. The same table shows the percent relative errors between the two methods, calculated according to equation (14):

$$|\delta U| = \frac{|U - U_g|}{U_g} \cdot 100 \quad (14)$$

Fig. 1 shows the graph of the relative error function calculated by the theoretical equation (13), and the experimental parameters used. This graph shows also the experimental relative errors calculated according to equation (14) and shown in Table I.

After a linear regression analysis of  $U$  and  $U_g$  values by the method of minimum squares was made, correlation coefficients were found( $r$ ), which was equal to 0.98902.



**Fig. 1 - Relative error in the measurement of moisture content ( $|\delta|$ ) as a function of wood moisture content ( $U$ ). The curve represents the theoretical error and the points indicated are the experimental deviations in the measurements carried out.**

**TABLE I. Moisture content values estimated by gravimetric ( $U_g$ ) and gamma ray attenuation methods and percent relative errors ( $|\delta U|$ ) between both.**

Sample No.	Gravimetric $U_g$ ( $\text{g.cm}^{-3}$ )	Gamma $U$ ( $\text{g.cm}^{-3}$ )	$ \delta U $ (%)
1	30.62	32.95	7.61
2	23.45	26.62	13.52
3	16.46	17.93	8.93
4	13.37	12.65	5.39
5	11.19	13.51	20.73
1	10.62	11.37	7.06
2	10.15	11.71	15.37
3	9.18	7.33	20.15
4	9.15	9.90	8.20
5	8.91	9.47	6.29

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