CLONAL AND ENVIRONMENTAL VARIATION OF STRUCTURAL TIMBERS OF
Eucalyptus FOR GROWTH, DENSITY, AND DYNAMIC PROPERTIES

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ABSTRACT: The main objective of *Eucalyptus* breeding programs for the pulp and paper industry is to produce varieties of trees with high levels of cellulose with the least possible amount of lignin. However, trees with these characteristics can be a major problem in the field, because of their fragility that makes them susceptible to breaking. The aim of this study was to investigate the clonal and environmental variation of the growth, wood density, and dynamic properties on large pieces of *Eucalyptus* wood by means of resonance technique. Here, we demonstrated that no other non-destructive technique is able to characterize the mechanical properties of wood so simply and rapidly at such low cost. The resonance technique provided a large, accurate data set of the key mechanical traits (such as the Young, the shear modulus and the loss tangent) of the wood even in lumber containing knots, small cracks and also slightly damaged areas. There were significant differences between clones and sites for height and circumference, and density of the trees. Using the dynamic elastic estimates, significant differences were detected between clones for all traits; however, no significant differences between sites were detected for dynamic modulus of elasticity. There were significant effect of interaction clone x site for circumference, height, density and shear modulus. These findings can be useful for screenings, classifications, or preliminary selections in breeding programs of *Eucalyptus*.

Key words: Acoustic, resonance, elastic properties, wood, lumber, hardwood.

VARIAÇÃO CLONAL E AMBIENTAL DE VIGAS DE *Eucalyptus* PARA CRESCIMENTO, DENSIDADE E PROPRIEDADES DINÂMICAS

RESUMO: *O objetivo principal dos programas de melhoramento genético de Eucalyptus para a indústria de celulose e papel é produzir variedades de árvores com níveis elevados de celulose e com a menor quantidade de lignina possível. No entanto, as árvores com estas características podem ser um grande problema em campo, devido à sua fragilidade que as torna suscetíveis à quebra. Este estudo foi realizado com o objetivo de investigar a variação do crescimento, da densidade da madeira e das propriedades dinâmicas por meio da técnica de ressonância em vigas de Eucalyptus em função dos clones e do ambiente. Os resultados mostram que nenhuma outra técnica não-destrutiva é capaz de caracterizar as propriedades mecânicas da madeira de forma tão simples, rápida e a baixo custo. A técnica de ressonância é capaz de estimar características mecânicas (como o módulo de elasticidade e de cisalhamento e o amortecimento interno) em grandes amostragens de madeira, mesmo com presença de nós, pequenas fissuras e também com áreas ligeiramente danificadas. Houve diferenças significativas entre os clones e os sítios para altura, circunferência e densidade da madeira das árvores. A partir das estimativas dinâmico-elásticas, foram detectadas diferenças significativas entre os clones para todas as características, no entanto, não houve diferenças significativas entre os sítios, para o módulo de elasticidade dinâmico. Houve efeito significativo da interação clone x site para a circunferência, altura, densidade e módulo de cisalhamento. Estes resultados podem ser úteis para a classificação ou a seleção preliminares em programas de melhoramento de Eucalyptus.*

Palavras-chave: Acústica, ressonância, propriedades elásticas, madeira, lenho, folhosas.

1 INTRODUCTION

The main objective of *Eucalyptus* breeding programs for the pulp and paper industry is to produce varieties of trees with high levels of cellulose with the least possible amount of lignin. However, trees with these characteristics can be a major problem in the field, because of their fragility that makes them susceptible to breaking.

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Natural vibration analysis is a simple and efficient way of characterizing the mechanical properties of many materials, including wood (BRANCHERIAU; BAILLERES, 2002; BUCUR, 1995). Using various species of wood, sample dimensions and growth conditions, several studies have shown a strong linear correlation between dynamic and static modulus of elasticity (ROSS et al., 1999; WANG et al., 2001; GREEN et al., 2004; BIBLIS et al., 2004).

Dynamic tests based on the resonance frequency have been applied successfully in order to analyze among other elastic properties, the dynamic modulus of elasticity of structural timber (HAINES; LEBAN; HERBE, 1996; BURDZIAK; NKWERA, 2002; OUIS, 1999; JIANG et al., 2010). To our knowledge, few studies were conducted in order to evaluate genetics aspects of the timber on the basis of their dynamic elastic properties. Thus, the aim of this study was to investigate the clonal and environmental variation of the dynamic properties on large pieces of *Eucalyptus* wood by means of resonance technique.

Here, we performed longitudinal and transversal dynamic tests on scantlings of clones of *Eucalyptus grandis* x *urophylla* hybrids from three contrasting clonal tests. The estimates of elastic traits based on resonance technique, in addition to the growth and density information for each tree, were used to assess the clonal and environmental variation of these traits.

2 MATERIAL AND METHODS

2.1 Wood sampling

In this study we evaluated 5 individuals of 10 clones (A, B, C… and J) of 6-years old *Eucalyptus grandis* x *urophylla* hybrids coming from three contrasting clonal tests (1, 2 and 3) established in Brazil (19°17' S, 42°23' W, alt 230-500 m), totalizing 150 trees. The main difference between clonal tests was the inclination of the plantations: the clonal test 1 had a slope of 40°, the clonal test 2 had a slope of 20° and clonal test 3 was plane (0°). The type of climate is Aw (Tropical savanna climate), according to the classification of Köppen (PEEL; FINLAYSON; MCMAHON, 2007), with mean annual rainfall of 1,205 mm. The mean annual temperature is around 25°C and the average annual humidity is 67.3%. The trees were planted in a randomized design and density of plantation was 1,667 trees/ha (3 m x 2 m spacing). Circumference at breast height (C) and commercial height (H) were measured before harvesting. Breast height wood disk was obtained from each tree and transported to the University of Lavras in Lavras, Minas Gerais State, Brazil. The commercial height

was considered when the diameter measured 7 cm.

A total of 410 pieces of wood with nominal sizes of 45 mm x 60 mm x 2,100 mm (hereafter referred to as 'scantlings') were taken from 150 central boards. Subsequently, the scantlings were kiln-dried at 14% (nominal) of moisture content under soft condition during two weeks. After the drying process the scantlings presented defects such as small cracks, checks and splits in their ends and, therefore, were trimmed to variable dimensions, depending of the extension of their defects. The clean scantlings had, in average, 1.54 meters of length, varying from 0.645 m to 2.080 (CV=16.9%) and the averaged width and thickness were, 60 mm and 43 mm, respectively, fluctuating slightly (CV=5.7% for width and CV=2.8% for thickness). Thus, all pieces were free of large fissures, biological affections, defects produced in the saw mill as severe reduction of width or thickness, but they presented knots and small cracks as well.

2.2 Dynamic tests on woods

The scantlings were submitted to transversal and longitudinal vibration tests. In transversal vibration, the first four modes of vibration were measured and used for estimating the dynamic transversal modulus of elasticity (E_T) of wood (also called modulus of Young), which represents its stiffness under bending stress, and the dynamic shear modulus (G). In longitudinal vibrations, the first vibration mode was measured and used for estimating the dynamic longitudinal modulus of elasticity (E_L) of wood, which represents its stiffness under compressive stress, and the loss tangent (tg δ), also called internal damping. The theoretical models of motion and their solutions used to estimate such elastic properties were deeply detailed in Brancheriau and Baillères (2002). These authors also provided a discussion about different theoretical models of motion; theirs approximate solutions and their respective hypotheses in longitudinal and transversal vibrations; and the effects of the elastic support required by BING system. The mass and the dimensions of each scantling were measured at the moment of the dynamic tests providing the weight density (ρ) of the wood samples. The error of measure was 0.1 g and 0.1 mm for mass and dimension, respectively. Figure 1 sums up the procedure of sample preparation and acoustic measurements.

2.3 Procedure of dynamic tests

The scantlings were placed on elastic supports so as to generate free vibrations. An exciting impulse was
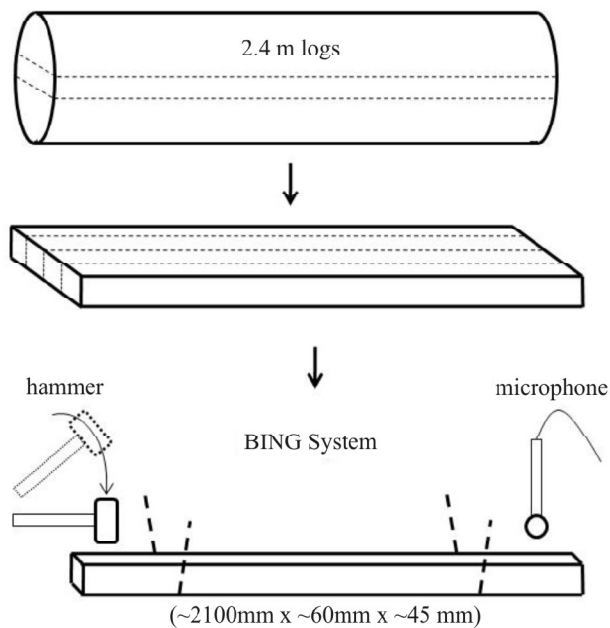
Figure 1 – Procedure of sample preparation and acoustic measurements.

Figura 1 – Procedimento de preparação de amostras e de medições acústicas.

produced by lightly striking the scantlings with an instrumented hammer at the opposite side of the output transducer (acoustic microphone). The transverse vibration was induced by an edgewise impact and the longitudinal vibration by an impact along the bound. The input and output signals were transmitted via a low-pass filter to an acquisition card on a computer and recorded as described in Brancheriau and Baillères (2003).

2.4 Parameter of dynamic tests

The analysis of the spectral signal, the selection of the peaks of the natural frequency of vibration of the wood samples and the estimates of the E_L, G, E_T and tg ä were performed using the software BING ® (CIRAD, Montpelier, France, version 9.1.3). The sampling frequencies of the signal were 78,125 Hz and 39,062 Hz for longitudinal and transversal vibration, respectively. The spectral acquisition was carried out by using 32,768 points for each test.

2.5 Statistic analysis

Analyses of variance for all observed values were performed according to the models in Eq. 1 using the

general linear model (GLM) procedure of the Statistical Analysis System (SAS INSTITUTE, 1990):

$$Y_{ij} = \mu + C_i + S_j + CS_{ij} + \varepsilon_{ij} \tag{1}$$

where Y_{ij} is the measurement of property ij, ì is the general mean, C_i is the fixed effect of Clone i, S_j is the fixed effect of Site j, CS_{ij} is the random effect of Clone i with Site j, and å$_{ij}$ is the error. The model assumes that the random factors are distributed normally with expectation zero.

3 RESULTS AND DISCUSSION

3.1 Dynamic properties and densities of the scantlings

Table 1 lists the descriptive statistics of the density and the dynamic elastic properties of scantlings of *Eucalyptus grandis* x *urophylla* wood. Based on early studies on dynamic tests of wood (HEARMON, 1948; ILIC, 2001; ILIC, 2003), we expected to find longitudinal elastic properties higher than the transversal ones. However, there was no statistically significant difference between averages of elastic modulus (Table 1). Some key factors affecting the transverse vibration were reported by Murphy (2000). In addition to these factors, according to Burdzik and Nkwera (2002) no method of elasticity measurement leads to the calculation of pure modulus of elasticity in bending, due to the presence of a shear component in the deflection of the specimen. We assume that the transversal vibrations are more sensible at the presence of knots and small cracks in the scantlings than longitudinal vibrations, especially for air-dried scantlings. The loss tangent values of the specimens were calculated from longitudinal test. As the software alerts us about imprecise estimations, we used only 328 values for tg ä$_L$ and 378 for shear modulus.

3.2 Correlations among scantlings properties

The correlations among growth, physical and elastic properties of 395 scantlings are listed in Table 2. Fifteen samples were considered as outliers, because their estimates yielded anomalous values. Circumference and height had a good correlation (0.83). Correlations between longitudinal and transversal dynamic elastic modulus were strong (0.953). It is well know that values of the modulus of elasticity increased with increasing wood density (KOLLMANN; COTÉ, 1968). According to the Table 2, the density of the scantlings showed good correlation with theirs elastic properties: 0.80 for E_L and 0.765 for E_T.

The E_L presented higher correlations with density than the E_T (Table 2). The main reason for this trend is the

Table 1 – Descriptive statistics of the density (ρ, kg m⁻³) and the dynamic elastic properties of the scantlings of *Eucalyptus grandis* x *urophylla*, including first resonant frequency (*f*, Hz), dynamic elastic modulus (E, MPa), specific modulus (E', MPa m³ kg⁻¹), loss tangent (tg δ, 10⁻³) and shear modulus (G, MPa) estimated by longitudinal (ₗ) and transversal (ₜ) vibration tests.

Tabela 1 – Estatística descritiva da densidade (ρ, kg m⁻³) e das propriedades dinâmico-elásticas das vigas de Eucalyptus grandis *x* urophylla, *incluindo a freqüência do primeiro modo de ressonância, (f, Hz), modulo de elasticidade dinâmica (E, MPa), módulo específico (E', MPa m³ kg⁻¹), atrito interno (tg δ, 10⁻³) e módulo de cisalhamento (G, MPa) estimados por testes longitudinais (ₗ) e transversais (ₜ).*

	ρ	f_L	E_L	E'_L	tg δ_L	f_T	E_T	E'_T	G_T
Average	547	1,618	12,825	23.43	7.74	98.27	13,278	24.3	693.69
Sd	65.8	346	2,565	2.98	1.74	49.04	2740	3.32	207.6
Min	383	1,027	7432	15.6	4.45	42.9	6,555	13.8	123
Max	776	3,414	21236	32.5	18.7	441.1	23,941	35.5	1,833
CV(%)	12	21.4	20	12.7	22.4	49.9	20.6	13.7	29.9
N	410	410	410	410	328	410	410	410	378

Table 2 – Correlations among growth, physical and dynamic elastic properties of the scantlings of *Eucalyptus grandis* x *urophylla* wood. The probability level for all relationships was <0.0001.

Tabela 2 – Correlações entre crescimento e propriedades físicas e dinâmicas das vigas de Eucalyptus grandis x urophylla. *O nível de probabilidade das correlações foi menor que 0,0001.*

	C	H	ρ	E_L	E'_L	tg δ	E_T	E'_T
H	0.83	1						
ρ	-0.23	-0.14	1					
E_L	-0.03	-0.01	0.80	1				
E'_L	0.14	0.09	0.02	0.82	1			
tg δ	-0.07	-0.08	0.06	-0.18	-0.34	1		
E_T	-0.06	-0.01	0.76	0.95	0.78	-0.20	1	
E'_T	0.096	0.05	-0.13	0.14	0.57	-0.14	0.82	1
G	-0.09	-0.08	0.35	0.28	0.14	0.03	0.18	0.10

lower uncertainty of measurement for longitudinal test. The higher correlations with density for E_L are in accordance to the findings of Ilic (2001), who tested small samples of *Eucalyptus delegatensis* R. Baker and found good correlations between air-dried density and longitudinal (0.83) and transversal (0.81) dynamic elastic modulus.

3.3 Genetic studies on wood quality

Analysis of variance (GLM) was performed to study clonal and environmental variation of a range of wood traits. Results of the analyses of variance are presented in Table 3. Significant differences between clones were detected for all traits. No significant differences between sites were detected for dynamic modulus of elasticity. There were significant effects of interaction clone x site for

circumference, height, density and shear modulus.

Figure 2 A presents the circumference at breast height (C) of the clones by the clonal tests 1, 2 and 3. The circumference of all clones increased from sites 1 to 3, except for the clone F, which had the lowest circumference in the site 3. The environmental negative effect on growth was stronger for clone C in the site 2, which produced the trees with small diameters (>60 cm), but the highest circumference for site 1 and 3.

Figure 2 B shows the mean wood density of clones by clonal test. The trees from site 1 produced the denser woods (573 kg m⁻³) while the clones from site 3 had the lowest wood density (518 kg m⁻³). Clearly, the trees that grow faster produce wood with lowest densities. The clones from test 1 had higher densities, except for clones C, D and

Table 3 – Analyses of variance (GLM) for growth, wood density and dynamic elastic properties of the scantlings of *Eucalyptus grandis* x *urophylla*.

Table 3 – *Análise de variância (GLM) para o crescimento, densidade da madeira e propriedades dinâmico-elásticas das vigas de* Eucalyptus grandis x urophylla.

	C (0.68)	H (0.51)	ρ (0.40)	E_L (0.22)	tg δ (0.18)	E_T (0.21)	G (0.16)
site	**	**	**	ns	**	ns	*
clone	**	**	**	**	**	**	**
interaction	**	**	**	ns	ns	ns	*

(* significative at 0.05 and ** significative at 0.001)
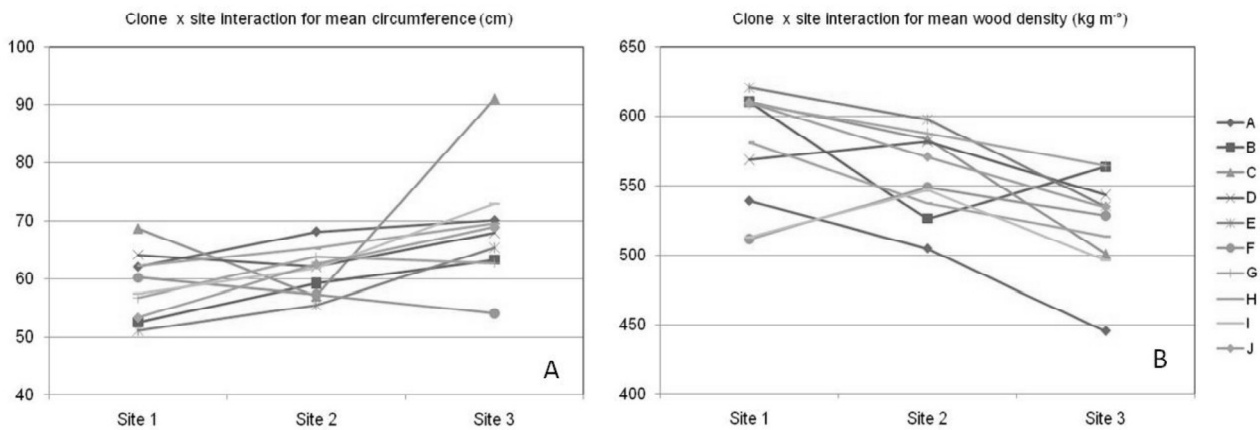
Figure 2 – Clone x site interaction for mean circumference (A) and for wood density (B).

Figura 2 – *Interação clone x sítio para circunferência média (A) e para densidade (B).*

F. Figure 3 A shows the dynamic modulus of elasticity in longitudinal test of the clones by clonal test (sites).

Table 3 shows that there was no environmental effect, but there were significant differences between clones for modulus of elasticity. For E_L and E_T (not shown) the clones presented stability between clonal tests, excepting the clones A, B, E and F which presented high variations. The differences between clones and clonal tests for dynamic modulus of shear are showed by Figure 3 B. The shear modulus of the clones was high (700 MPa) in the site 1, except for the clones B, D and I. Tukey (HSD) multiple range tests for growth, wood density and dynamic elastic properties of the scantlings by clone and by site are presented in Table 4.

3.4 Advantages for breeding selection

The early studies on genetics of *Eucalyptus* concentrated on tree growth, survival, stem straightness and branch quality. As breeding programs progressed the range of traits assessed increased to include fitness, which relate to the ability of trees to survive environmental threats, and to quality, of which those pertaining to wood quality are amongst the most important (GREAVES, BORRALHO; RAYMOND, 1997). In addition, the traditional methods of assessment for wood quality traits are expensive and restrict the numbers of samples that can be processed (RAYMOND, 2002). Here, we demonstrated that no other non-destructive technique is able to characterize the mechanical properties of wood so simply and rapidly at such low cost. The resonance technique enabled us to rapidly estimate key mechanical properties (such as the Young, the shear modulus and the loss tangent) of the wood even in lumber containing knots, small cracks and also slightly damaged areas.
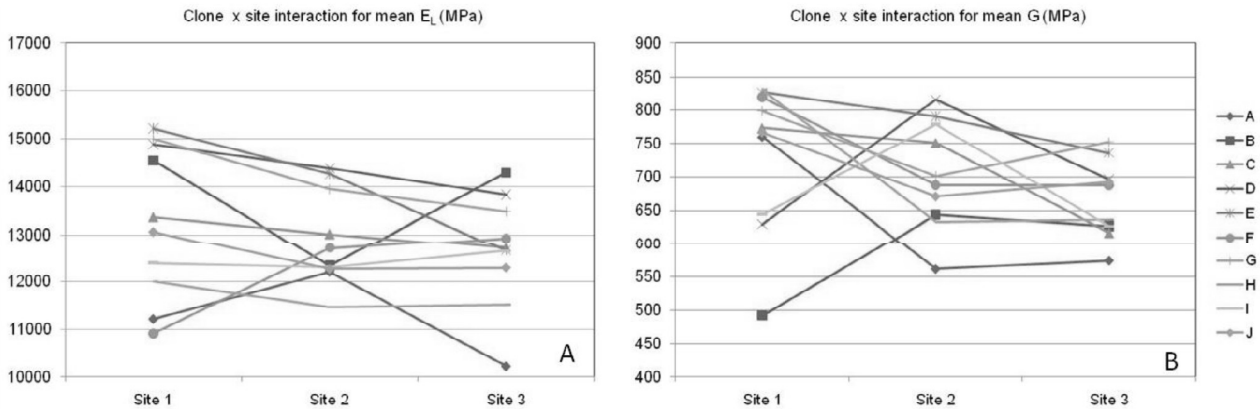
Figure 3 – Clone x site interaction for dynamic modulus of elasticity in longitudinal test (A) and for dynamic modulus of shear in transversal test (B).

Figura 3 – Interação clone x sítio para módulo de elasticidade dinâmico médio (A) e para módulo de cisalhamento (B).

Table 4 – Tukey (HSD) multiple range tests for growth, density and dynamic elastic properties of the *Eucalyptus* scantlings.

Tabela 4 – Teste de média de (Tukey, HSD) para crescimento, densidade e propriedades dinâmico-elásticas de vigas de Eucalyptus.

Clone	C (cm)		H (m)		ρ (kg m⁻³)		E_L (MPa)		tg δ (10⁻³)		E_T (MPa)		G (MPa)	
A	66.8	B	23.6	CB	496.6	FE	11254	D	7.25	ABC	11801	D	625.6	B
B	59.2	D	21.7	ED	560.2	ABCD	13636	ABC	8.16	ABC	14906	A	599.3	B
C	77.8	A	26.0	A	546.9	BCDE	12934	ABCD	7.82	ABC	13301	BDC	680.0	AB
D	64.7	BC	23.3	CBD	564.7	ABCD	14272	A	7.96	ABC	14639	AB	728.5	AB
E	58.3	D	21.1	E	578.4	AB	13877	AB	7.07	BC	14269	BC	778.1	A
F	57.7	D	21.8	ED	528.8	DEF	11959	CD	8.37	AB	12421	C	742.8	AB
G	61.5	CD	22.2	CDE	586.5	A	14131	AB	7.88	ABC	14515	AB	741.5	AB
H	66.1	BC	22.8	CBD	540.2	CDE	11638	D	8.55	A	12114	D	689.6	AB
I	64.5	BC	24.1	B	518.3	FE	12451	BCD	6.95	C	12593	C	678.2	AB
J	62.3	BCD	22.9	CBD	568.5	ABC	12490	BCD	7.58	ABC	12833	BC	705.2	AB
Site	C (cm)		H (m)		ρ (kg m⁻³)		E_L (MPa)		tg δ (10⁻³)		E_T (MPa)		G (MPa)	
1	59.8	B	21.2	B	573.4	A	13044	A	8.38	A	13355	A	742.2	A
2	61.6	B	23.7	A	558.5	A	12930	A	7.56	B	13528	A	700.1	AB
3	72.0	A	24.3	A	518.0	B	12610	A	7.45	B	13042	A	653.3	B

4 CONCLUSION

There were significant differences between clones and sites for height and circumference, and for density of the trees. Using the dynamic elastic estimates, significant differences were detected between clones for all traits. No significant differences between sites were detected for dynamic modulus of elasticity. There were significant effects of interaction clone x site for circumference, height, density and shear modulus. In short, the BING system rapidly provided a large accurate data set of mechanical wood properties as required for high-throughput phenotyping of genetic approaches. These results can be useful for initial classifications, screenings or preliminary selections in breeding programs of *Eucalyptus*. As reported by Burdzik and Nkwera (2002), this method proved to be

fast, highly repeatable and does not require heavy equipment, making it the ideal method for on-site determining of MOE at the sawmill.

5 ACKNOWLEDGEMENT

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