REAL-TIME MEASUREMENT OF VIBRATIONAL PROPERTIES OF GREEN WOOD AT HIGH TEMPERATURE[1]

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ABSTRACT

To obtain basic data for high-temperature drying of wood, changes in vibrational properties of green wood of Sitka spruce (*Picea sitchensis* Carr.) in a high-temperature atmosphere were measured *in situ*. Young's modulus and loss tangent were measured with vibration tests in an electric oven. Changes in temperature, moisture content, specific Young's modulus, and loss tangent with time were obtained. These changes were investigated by dividing them into four stages.

Keywords: Real-time measurement, vibrational properties, green wood, high-temperature drying.

INTRODUCTION

There have been many studies on the method to dry wood quickly (Sumi 1978, 1982; Shida 1996; Kubojima et al. 1998; Nakashima et al. 1999; Yoshida et al. 1999; Kubojima and Shida 2001), and high-temperature drying of wood is gradually coming into widespread practice. This is because the high-temperature drying, which makes it possible to dry wood in a short time, is expected to lower drying cost.

However, when wood is dried quickly at high temperature, many types of damage such as checks, splits, and honeycombs tend to occur. Therefore, a heating technique to guarantee both drying speed and quality of wood products is needed.

In order to develop this technique, the change in wood during high-temperature drying should be studied. For this purpose, it is important to understand basic wood properties when water is lost by heating.

The wood property that relates to the checks directly is work before rupture, in other words, relationship of stress-strain. Wood deformation under the influence of external force consists of elastic deformation and flow one. One of the wood properties that relates to such wood deformation and can be measured simply *in situ* is viscoelasticity. We have already measured the viscoelasticity of oven-dried wood specimens with a vibration test while the specimens are heated from room temperature to 200°C (Kubojima et al. 2001).

[1] This research was presented in part at the 50th annual meeting of the Japan Wood Research Society in Kyoto, April 2000.

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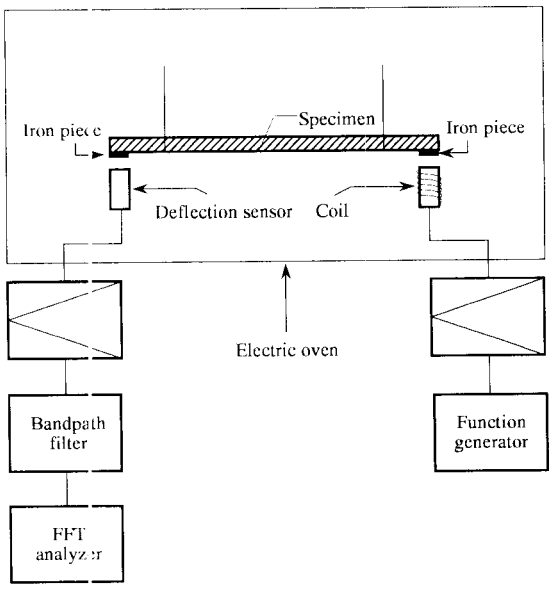

FIG. 1. Apparatus for vibration test.

In this study, real-time measurements of changes in the viscoelasticity of green wood during heating were studied, and summaries of the changes were obtained. These results are useful as the first step for explaining the mechanism of the occurrence of the damage and for finding the optimum treatment condition to control the damage.

EXPERIMENT

Specimens

Sitka spruce (*Picea sitchensis* Carr.) green wood (moisture content: 55–120%) was used for this study. The dimensions of the specimens were 200 mm in length (longitudinal direction) by 25 mm in width (radial direction) by 10 mm in thickness (tangential direction) for L-direction specimen and 120 mm in length (radial direction) by 25 mm in width (longitudinal direction) by 10 mm in thickness (tangential direction) for R-direction specimen. Specimens for measuring temperature, weight and dimensions, and vibrational properties were matched in width direction. After absorbing water, the specimens were heated at each designated temperature (100°C, 150°C, and 200°C) and then they were oven-dried at 105°C. Values for the minimum, maximum, and average moisture content directly before heating were 85%, 134%, and 113%, respectively.

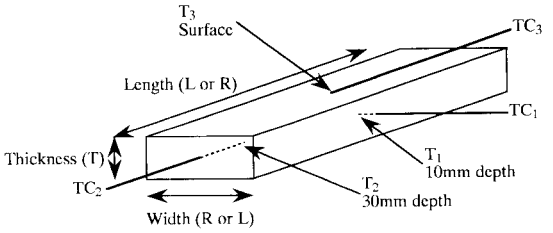

FIG. 2. Measurement of the surface and interior temperatures of the specimens.

Vibration test

To obtain Young's modulus E and loss tangent tanδ, the free-free flexural vibration test was conducted. In this test, each end of a specimen is regarded as a free end, that is to say, both bending moment and shearing force are zero at each end. The same apparatus as in the previous study (Kubojima et al. 2001) was used (Fig. 1). The test beam was suspended by two wires of 0.12-mm diameter at the nodal positions of the free-free vibration corresponding to its first resonance mode. It was excited in the direction of thickness at one end by a magnetic driver. The motion of the beam was detected by a deflection sensor at the other end. The signal was processed through a fast Fourier transform (FFT) digital signal analyzer.

The value of E was calculated from Euler-Bernoulli's equation and tanδ from the width at −6 DB from the peak of the resonance curve. The dimensions of specimens were regarded as constant during the heating. It took 100s to draw a resonance curve.

Measurement of wood properties during heating

The temperatures were measured at 3 points with T-type thermocouples (Fig. 2). The thermocouple 1 (TC_1) was inserted in width di-

rection at a depth of 10 mm from the central point of the length × thickness plane, TC_2 was inserted in length direction at a depth of 30 mm from the central point of the width × thickness plane, and TC_3 was installed on the central point of the length × width plane. The temperatures of TC_1, TC_2, and TC_3 are indicated as T_1, T_2, and T_3, respectively. When the vibration test was conducted, only one thermocouple to indicate the temperature in the oven was used.

To measure the dimensions and weight, the specimens were taken out of the oven after reaching constant temperature.

In the vibration tests, a specimen, its supporting system, the magnetic driver, and the deflection sensor were set in an electric oven as shown in Fig. 1. After the vibration test at room temperature (about 20°C), the temperature was raised to the designated temperature. The vibration tests were conducted at the beginning of heating and were continued at intervals of 5 to 20 min. After heating, the specimens were oven-dried at 105°C, and then the vibration tests were conducted at room temperature.

The measuring system was not sealed, and the humidity in the oven was not adjusted during the heating because there were small openings for cables of the magnetic driver and the deflection sensor.

RESULTS AND DISCUSSION

Figures 3–5 show the changes in the temperature, the moisture content, the specific Young's modulus, and the loss tangent during the heating.

Temperature

The changes in the temperatures could be roughly divided into the following four stages. The boundary times between adjacent stages are shown in Table 1. The temperatures at all 3 locations (10-mm depth T_1, 30-mm depth T_2, surface T_3) rose in the 1st stage. In the 2nd stage, they were constant or rose more slowly than in the 1st stage. They began to rise in the 3rd stage faster than in the 2nd stage. At the 4th stage, they were constant near each designated temperature.

There was a clear tendency that T_2s of all the L-direction specimens were lower than T_1s at the 2nd stage. In the R-direction specimens, the differences between T_1 and T_2 were smaller than in the L-direction specimens. This may have been caused by an inclination of moisture content in the L-direction because moisture diffuses mainly in the L-direction during the drying of wood. The L-direction distance between TC_1 and TC_2 was about 70 mm, while in the R-direction specimen it was about 2.5 mm. Hence, the difference in moisture content between the places where TC_1 and TC_2 were installed was larger in the L-direction specimens than in the R-direction specimens.

It is thought that the behavior of T_1 and T_2 in the L-direction specimen should normally be as follows: If the moisture content directly before heating MC_i is uniform in a specimen, both T_1 and T_2 have a plateau region, and the plateau region of T_1 is longer than that of T_2 because the moisture content near the center part where TC_1 is installed is higher than that near the end part where TC_2 is installed during heating. However, in this study, water was absorbed in the specimens before the heating, and MC_i became 113% on average. So, it is possible that the moisture content was higher near the end part than at the center part. It is thought that the plateau region of T_1 did not occur because of this lower moisture content in the center.

We tried applying the time zones defined by the temperature changes to the behavior of the moisture content and the vibrational properties.

Moisture content

The moisture content fell with time monotonically and became fiber saturation point (FSP) at the end of the 2nd stage or the beginning of the 3rd stage. This tendency was not influenced by MC_i, which ranged from 85 to 134%.

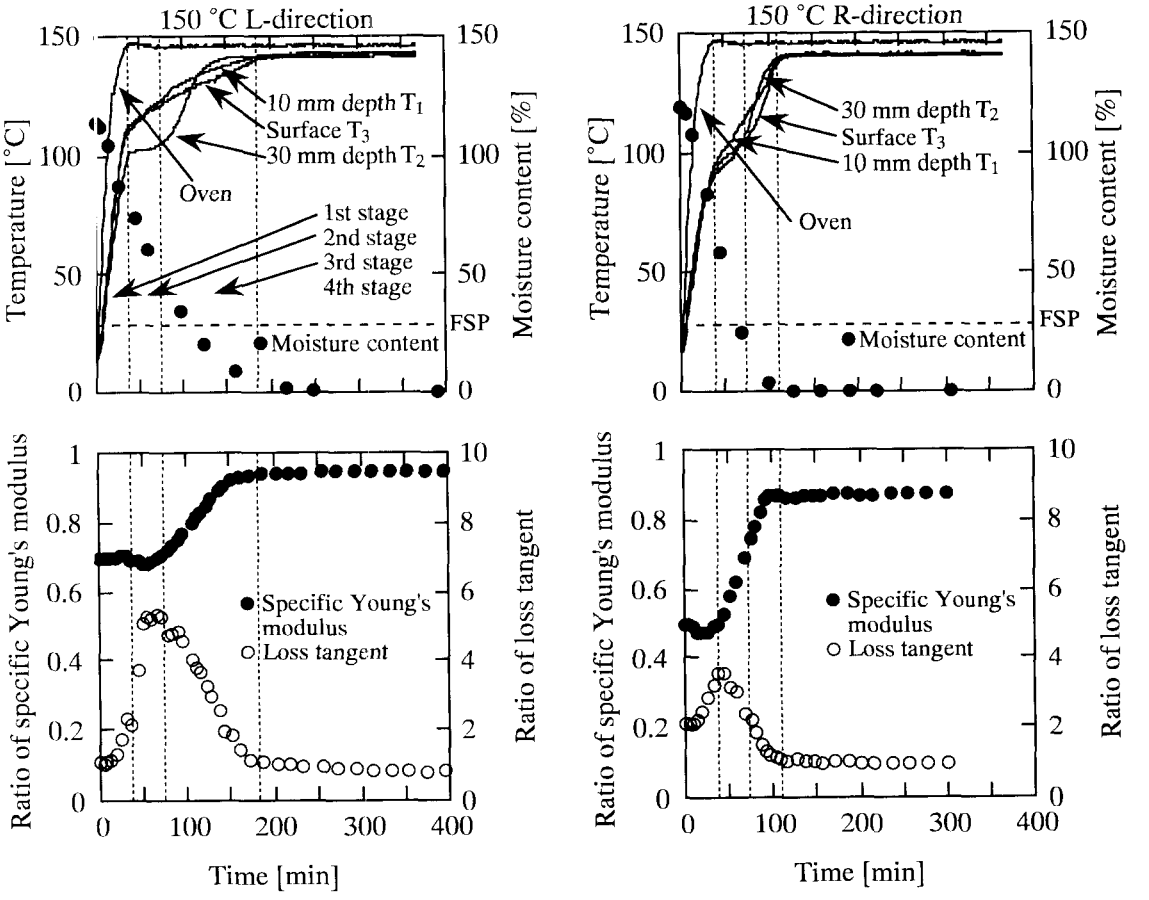

FIG. 3 Changes in temperature, moisture content, specific Young's modulus, and loss tangent during heating. The designated temperature is 150°C. Changes in specific Young's modulus E/ρ and loss tangent $\tan\delta$ are expressed using the ratio based on these values, $(E/\rho)/(E/\rho)_0$ and $\tan\delta/\tan\delta_0$, respectively. Suffix 0 means the oven-dried values after the heating shown in Table 2.

Vibrational properties

The vibrational properties of oven-dried specimens measured at room temperature after the heating at each designated temperature are tabulated in Table 2. The changes in specific Young's modulus E/ρ and $\tan\delta$ are expressed using the ratio based on these values, $(E/\rho)/(E/\rho)_0$ and $\tan\delta/\tan\delta_0$, respectively, where the suffix 0 means the oven-dried values after the heating shown in Table 2.

The value of E/ρ was stable or had a minimum at the 1st or the 2nd stages, increased at the 3rd stage, and then became stable at the 4th stage. On the other hand, $\tan\delta$ increased at the 1st stage, became stable or had a peak at the 2nd stage, decreased at the 3rd stage, and became constant at the 4th stage.

At the 3rd stage, honeycombs were observed on the RT-planes of all the specimens for measuring dimensions and weight. If the damage is serious, E/ρ must decrease and $\tan\delta$ increase at this stage. However, E/ρ increased and $\tan\delta$ decreased. This means that the damage was so small that it had little effect on the vibrational properties.

In the case of the 200°C specimen, the specific Young's modulus in R-direction E_R/ρ reached a maximum before stabilizing at the 4th stage. This is explained as follows: In the previous study (Kubojima et al. 2001), using

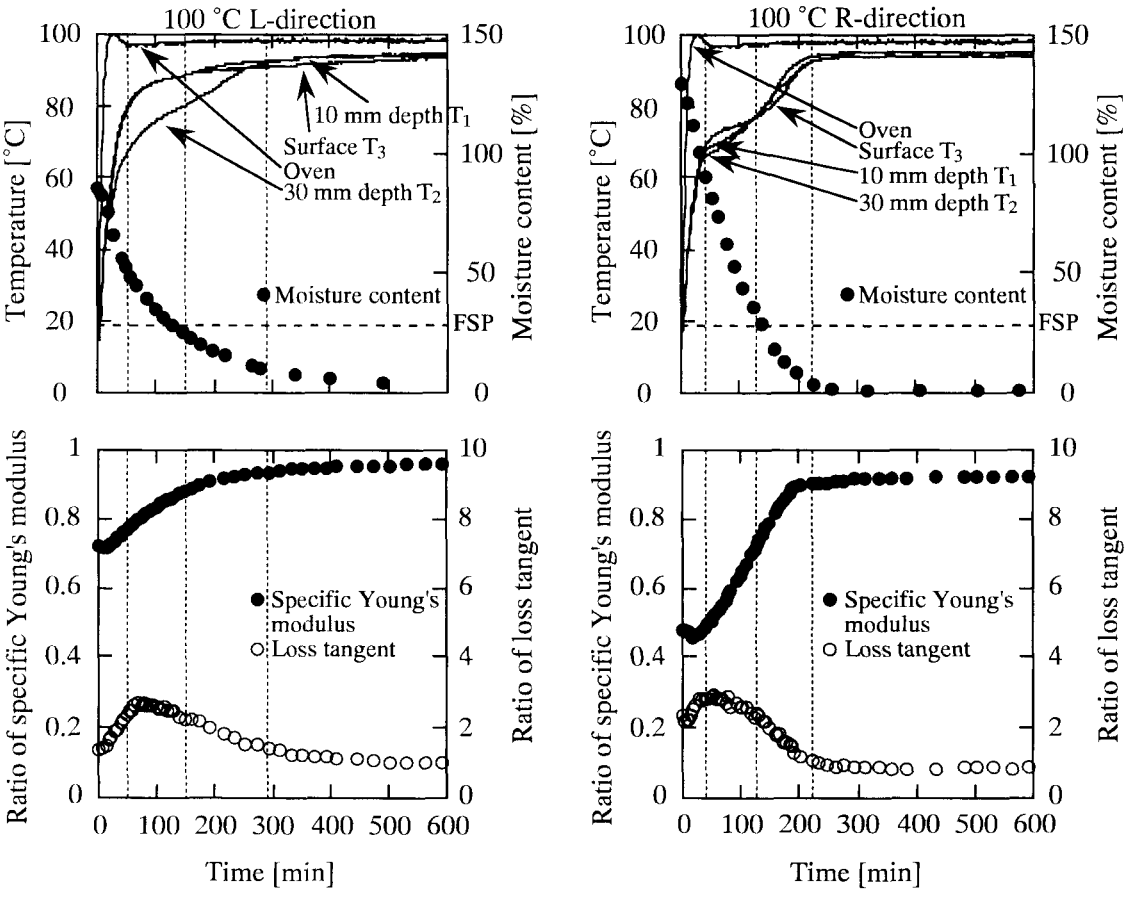

FIG. 4. Changes in temperature, moisture content, specific Young's modulus, and loss tangent during heating. The designated temperature is 100°C. Changes in specific Young's modulus E/ρ and loss tangent $\tan\delta$ are expressed using the ratio based on these values, $(E/\rho)/(E/\rho)_0$ and $\tan\delta/\tan\delta_0$, respectively. Suffix 0 means the oven-dried values after the heating shown in Table 2.

oven-dried woods as specimens, E_R/ρ decreased most in the temperature range of 150 to 200°C. The phenomenon in this study may have been caused by the temperature rising from 150 to 200°C though moisture content was falling.

From the changes in E/ρ and $\tan\delta$ with the time mentioned above, the behavior of $\tan\delta$ corresponded to that of the temperature, especially T_2: each stage of $\tan\delta$ corresponded to that of T_2, while 1st and 2nd stages of E/ρ did not correspond perfectly.

Let us now examine the change in $\tan\delta$. We consider that $\tan\delta$ keeps a constant value over FSP not only at room temperature (Kôllmann and Krech 1960) but also at high temperature since the loss tangent in L-direction $\tan\delta_L$ was stable at the 2nd stage of the 150°C drying. Then, the change in $\tan\delta$ can be explained as follows:

At the 1st stage, $\tan\delta$ increased because of the thermal softening, some mechanosorptive effects of swelling wood, and the moisture content higher than FSP even while the moisture content was changing. At the 2nd stage, it tended to be constant since the temperature was stable and the moisture content was over FSP though moisture content continued to change. It is thought that the appearance of the plateau region or the peak of $\tan\delta$ depends on

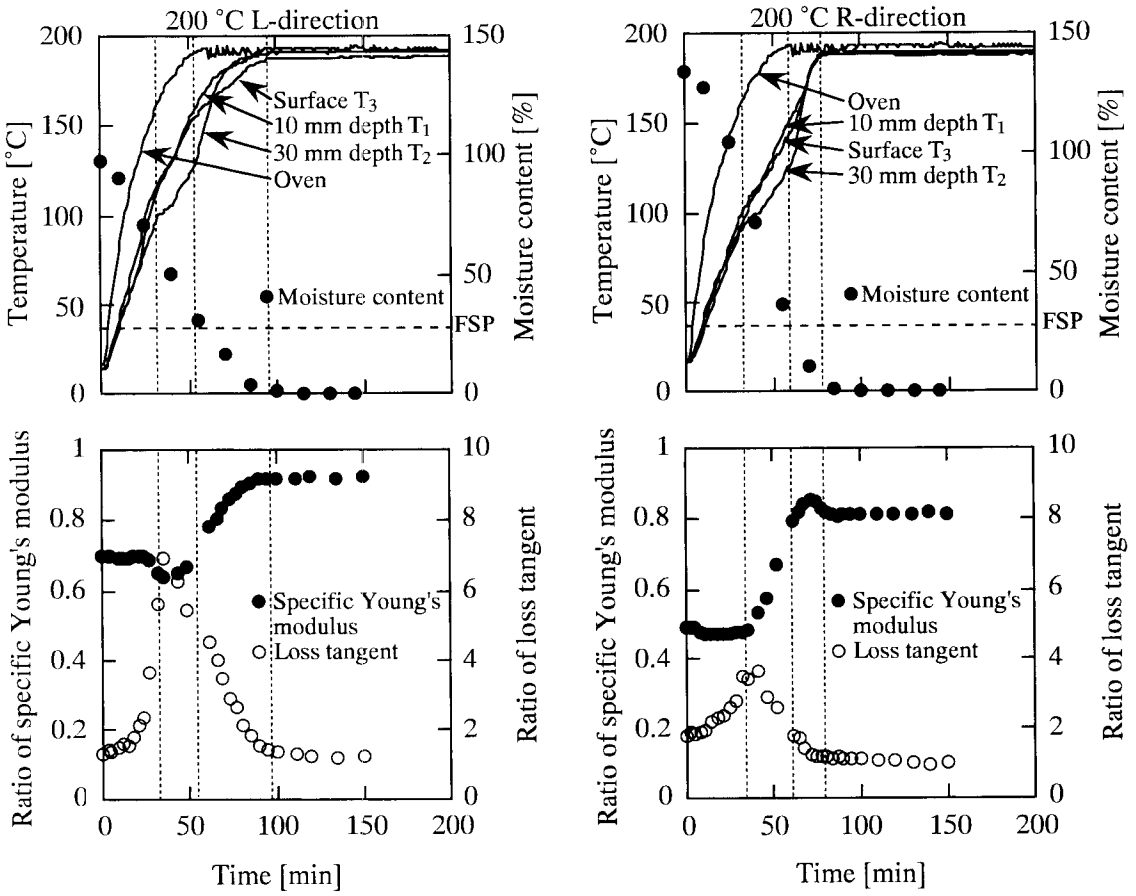

FIG. 5. Changes in temperature, moisture content, specific Young's modulus, and loss tangent during heating. The designated temperature is 200°C. Changes in specific Young's modulus E/ρ and loss tangent $\tan\delta$ are expressed using the ratic based on these values, $(E/\rho)/(E/\rho)_0$ and $\tan\delta/\tan\delta_0$, respectively. Suffix 0 means the oven-dried values after the heat ng shown in Table 2.

TABLE 1. *Boundary time between adjacent stages.*

Specimen	t_{12} [min]	t_{23} [min]	t_{34} [min]
100°CL	48	143	280
100°CR	37	130	224
150°CL	36	65	183
150°CR	33	73	105
200°CL	33	54	97
200°CR	34	56	81

Notes: t_{12}, t_{23}, t_{34} means the boundary time between the 1st and 2nd stages, 2nd and 3rd stages, and 3rd and 4th stages, respectively. L and R mean the L-direction and R-direction, respectively.

TABLE 2. *Vibrational properties of oven-dried specimens measured at room temperature after heating.*

	Designate temperature [°C]		
	100	150	200
Specific Young's modulus [GPa]			
L-direction	24.5	31.3	32.9
R-direction	2.1	2.1	2.0
Loss tangent [$\times 10^{-3}$]			
L-direction	7.9	7.9	6.4
R-direction	18.0	19.9	21.6

the length of the 2nd stage: When the 2nd stage is long, that is to say, MC_i is high, the plateau region appears, and when it is short, that is, MC_i is low, the peak appears. At the 3rd stage, if temperature rises, tanδ must increase (James 1961; Kubojima et al. 2001), but if moisture content falls below FSP, tanδ must decrease. The fact that tanδ decreased indicates that the change in tanδ was influenced by the moisture content rather than temperature, because the part where the moisture content was below FSP in the specimen increased at the 3rd stage. As for this stage, the change in E/ρ was not inconsistent with tanδ. At the 4th stage, tanδ became constant since temperature and the moisture content (below FSP) were stable.

These results indicate that some factors that influence tanδ of wood during drying may be the temperature and moisture content. If so, tanδ during drying can be expressed by the interaction of those two terms. At the 1st and 2nd stages, the contribution of the temperature to tanδ is thought to be more than that of moisture content, while at the 3rd stage, the contribution of the moisture content may be larger than the temperature. Further experiments, for example, measuring vibrational properties under various temperature and moisture content conditions, and obtaining data on the variation of the temperature and moisture content in the specimen, are needed to simulate tanδ during drying.

Each stage of the change in tanδ, but not always that of E/ρ, corresponded to each stage of the change in the temperature as mentioned above, and the reason for this was not understood in this study. Thus, further investigation is required.

CONCLUSIONS

Changes in the vibrational properties of green wood during high-temperature drying were measured in real-time, with the following results: 1) The change in temperature was roughly divided into four stages. 2) Moisture content decreased to FSP late in the 2nd stage or early in the 3rd stage. 3) Both E/ρ and tanδ were influenced by the changes in temperature and moisture content during the heating. Each stage of the change in tanδ, but not always that of E/ρ, corresponded to each stage of the change in the temperature, especially for T_2. 4) It appears that tanδ depended on the temperature rather than the moisture content at the 1st and 2nd stages, while it was subject to the moisture content rather than the temperature at the 3rd stage.

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