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MOISTURE DEPENDENCE OF IMPACT RUPTURE PROPERTIES OF PAPER

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THERE are a number of studies on the relationship between the mechanical properties of paper and adsorbed water. In other previous papers—Anderson,[1] Yoshino[2] and Kadoya[3]—which concerned moisture dependence of mechanical properties of paper under impact conditions, it was found that the maximum values in the impulse or rupture energy existed at 15–18 per cent moisture content. The reason why such a maximum value exists is, however, left unsolved, because of the complexity of failure mechanism under impact conditions.

The purpose of this study is to clarify how adsorbed water influences the impact behaviour of paper. Static measurement (stress relaxation) under various relative humidities was investigated for the sake of comparison.

The hand-sheets used in this study were made from bleached softwood kraft pulp, beaten by a PFI mill. A sheet was cut into strips of 13·5 cm in length, and 1·5 cm in width (span: 10 cm). The strips were conditioned at 100 per cent RH and 20° C for a week to eliminate the effect of the internal stress—Johanson and Kubat.[4] After that they were placed for 10 days at 20° C in desiccators adjusted to a constant relative humidity of 20, 44, 53, 60, 65, 76, 81, 84, 93, 97, and 100 per cent by the use of saturated salt solutions. The sample after conditioning was immersed in paraffin liquid and then subjected to impact test as soon as possible. When the load/elongation curves of the samples immersed in paraffin liquid were compared with those of control, no effect of the treatment with paraffin liquid on the sheet was detected.

The apparatus used was a shalpy type tester which was improved to measure the impact elongation of paper in the longitudinal direction, as shown in Fig. 1. The acceleration transducer was attached to the hammer of this pendulum type dynamic tester. The output pulse from the acceleration

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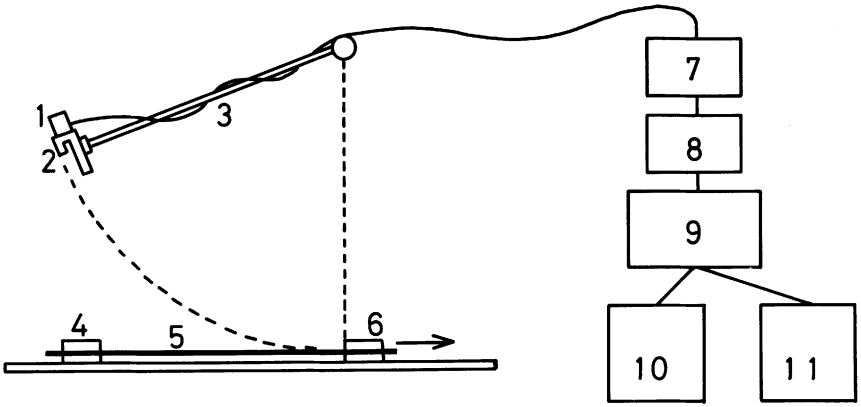

Fig. 1—Schematic diagrams of the impact tester
1. acceleration transducer, 2. hammer, 3. shaft, 4. fixed clamp, 5. sample, 6. moving clamp, 7. bridge box, 8. dynamic strain amplifier, 9. transient time converter, 10. recorder, 11. synchroscope

transducer at the instant of impact was expanded in the time scale by a thousand fold using a transient time converter.

Fig. 2 shows the change of hammer acceleration at the instant of impact against time for the bleached soft wood kraft pulp sheet conditioned at 65 per cent RH (solid line), and the change of hammer acceleration when the moving clamp only was hit by the hammer, i.e. sample absent (broken line). The abrupt change in acceleration in the initial stage is due to the hammer hitting the moving clamp (the broken line is very similar to the solid line). In the case of the sample being present, the acceleration change which shows the vibration behaviour following the abrupt change was attributed to change with sheet failure. Three reasons are possible for interpreting such vibrational behaviour of the output: (1) it is due to the characteristic of the acceleration transducer itself, (2) until the sheet is broken completely, the hammer hits the moving clamp several times because of strong vibration in the sample, (3) it is due to bending of the shaft holding the hammer at the instant of impact. The third case seems to be the cause of vibration because, the output from the acceleration transducer is secured against saturation up to 3 KHz, the output in the test carried out without the sample also shows vibration and the period of vibration in both cases of presence and absence of the sample is very similar. The vibration thus seems to be inherent of the shaft.

There is a need to define a starting point of deformation and an end point of failure on the curve showing the change of acceleration with time. When,

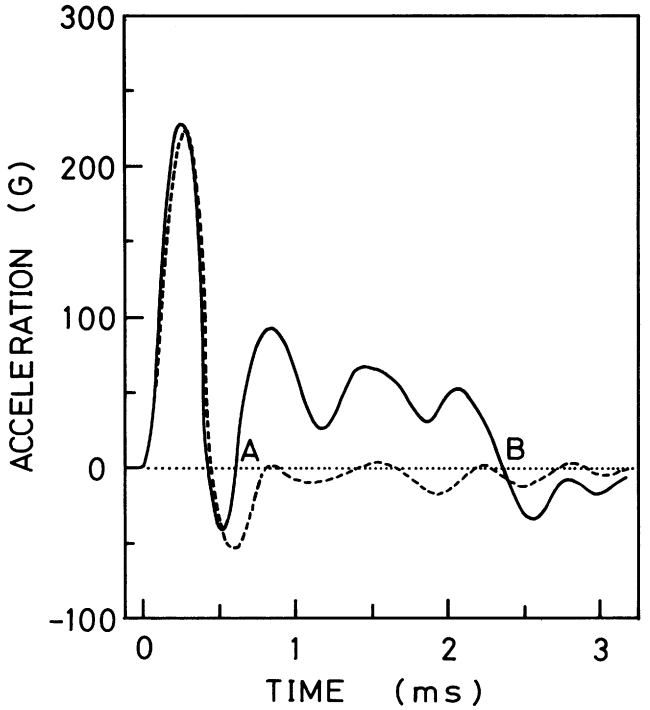

Fig. 2—Time dependence of the hammer acceleration for bleached softwood kraft pulp
Dashed line: blank test (moving clamp only was hit with the hammer)

in Fig. 2, hammer velocity at point A is designated as V_A, that at point B as V_B, respectively, the absorption energy is given as follows,

$$E_1 = \tfrac{1}{2}m(V_A{}^2 - V_B{}^2),$$

where m = weight of hammer.

V_A and V_B were obtained by integration on the curve showing the change of acceleration with time. The difference between the swing angle of hammer (α) after the failure of the sheet and the angle of the blank test (β) can also lead to the absorption energy, E_2.

$$E_2 = \mathrm{ml}(\cos\alpha - \cos\beta),$$

where l = shaft length.

The relationship between both energies is represented as $E_1 = (1+0{\cdot}05)E_2$, over the whole humidity range. Therefore, it might be appropriate to

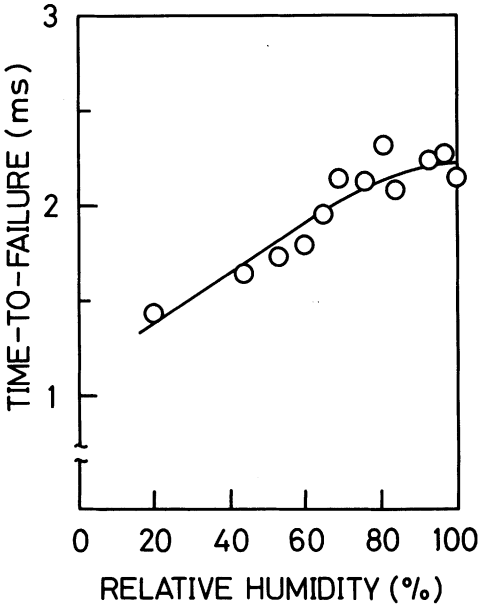

Fig. 3—Time-to-failure *vs.* relative humidity curve of bleached softwood kraft pulp

consider conveniently point A as the starting point of the breakage and point B as the end of failure.

Figs. 3 and 4 show the results of moisture dependence of time-to-failure and strain-to-failure, respectively. From these figures it is clear that under the impact conditions, time-to-failure does not correspond to strain-to-failure above 80 per cent RH. Time-to-failure appears to level off to 2·3 msec above 80 per cent RH, though the rate of increase in strain-to-failure against humidity above 80 per cent RH is somewhat higher than that below 80 per cent RH as shown in Fig. 4. Under the static stress–strain test, time-to-failure corresponds completely to strain-to-failure. These results may lead to a concept that the rupture mechanism under impact conditions at higher than 80 per cent RH is different from that at lower humidity.

Fig. 5 shows the failure zone of samples conditioned at 97 per cent RH and 53 per cent RH respectively. The former is more fuzzy than the latter. At higher than 80 per cent RH, it was observed very frequently that the load after failure of the sheet did not reach zero as shown in Fig. 6(a), and the sample was not completely separated into two pieces after failure, as shown

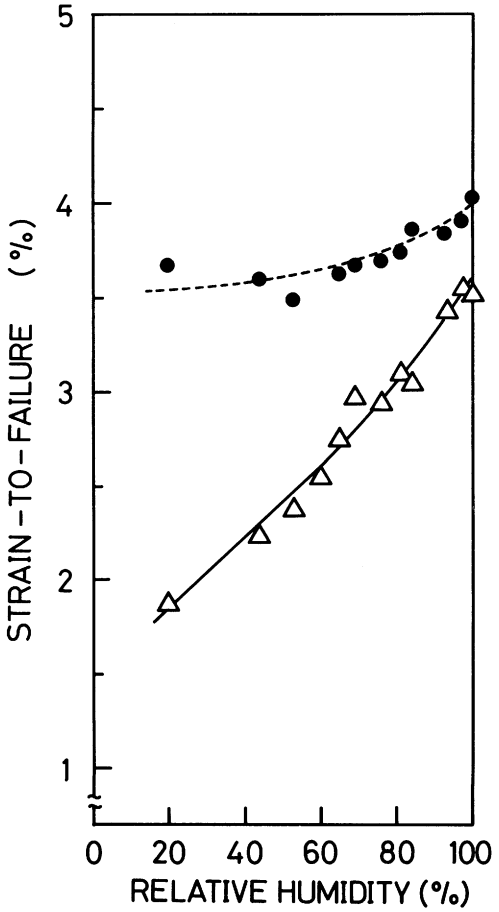

Fig. 4—Strain-to-failure *vs.* relative humidity curves of bleached softwood kraft pulp. △ ——— △: under impact condition, ● - - - - ●: under static condition

in Fig. 6(b). These seem to be due to the slippage of fibres during deformation.

Figs. 7 and 8 show the results of moisture dependence of the impulse and the absorption energy, respectively, in which the maximum appears at 70–80 per cent RH. These tendencies are in good agreement with the ones in other previous papers.

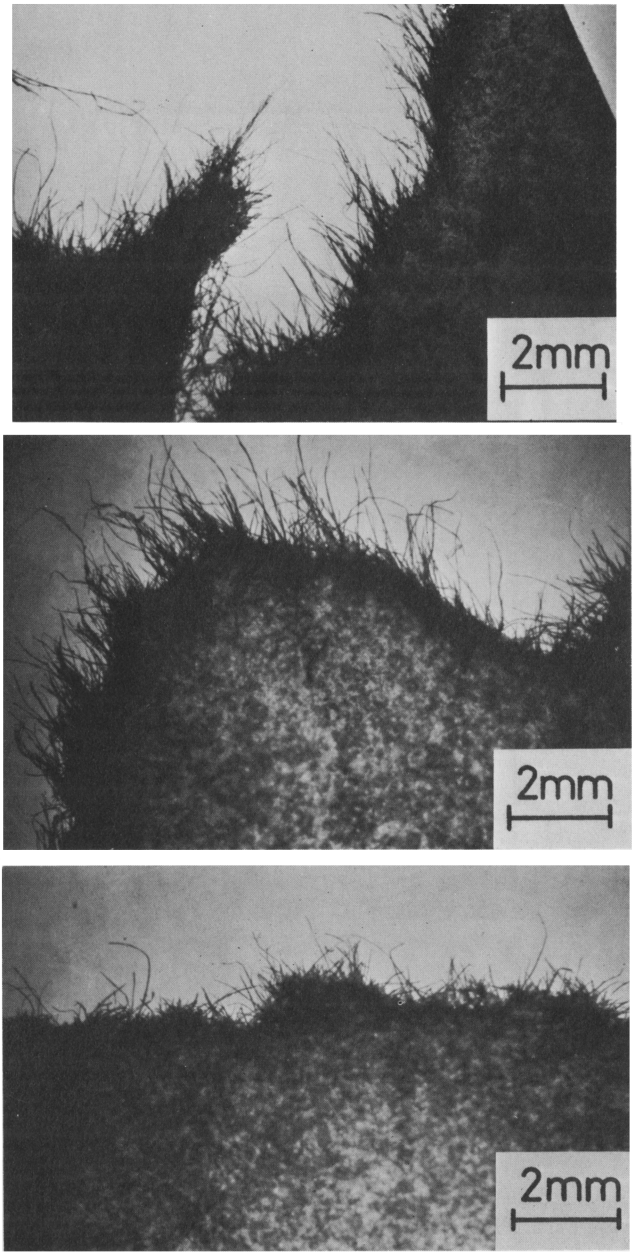

Fig. 5—Photographs of bleached softwood kraft pulp failured by impact elongation
(a), (b): conditioned at 97 per cent R.H., (c): conditioned at 53 per cent R.H.

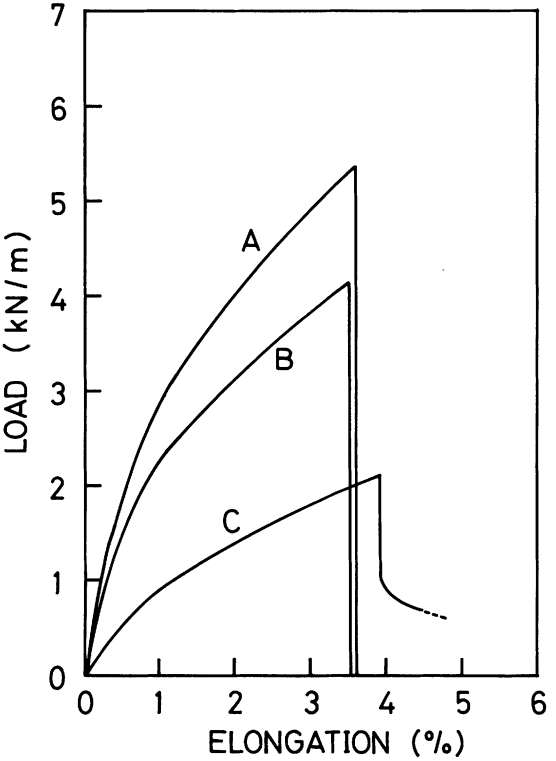

Fig. 6(a).—Tensile stress strain curves of bleached softwood kraft pulp for various moisture content levels
A: 20 per cent R.H., B: 53 per cent R.H., C: 97 per cent R.H. (rate of elongation: 4 mm/min, span: 100 mm)

The absorption energy of cellophane as a function of relative humidity is shown in Fig. 9. In spite of scattering values, a maximum in absorption energy was found also in the vicinity of 70–80 per cent RH. This result is very similar to that of paper. Therefore, a similar mechanism of energy absorption probably acts in both cases.

It is generally recognised that in the case of the impact test, a strong vibration arises in a sample and the internal friction in a vibrating body is a very important factor of the energy absorption mechanism. The internal friction of cellulose molecules may be, consequently, concerned with the energy absorption mechanism of paper too. Kubát and Lindbergson[5]

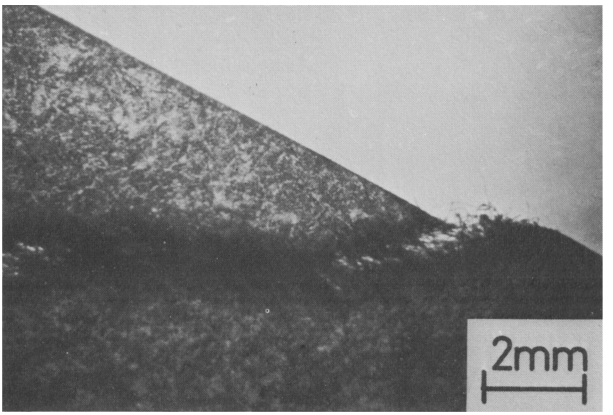

Fig. 6(b)—Photograph showing the failure spot of bleached softwood kraft pulp conditioned at 97 per cent R.H. under static elongation

showed that the loss factor (tan δ) of paper increased with increasing moisture content up to 80 per cent RH. This fact seems to be one of the reasons why in the impact measurement of paper, the absorption energy or impulse increases with increasing relative humidity up to 80 per cent RH.

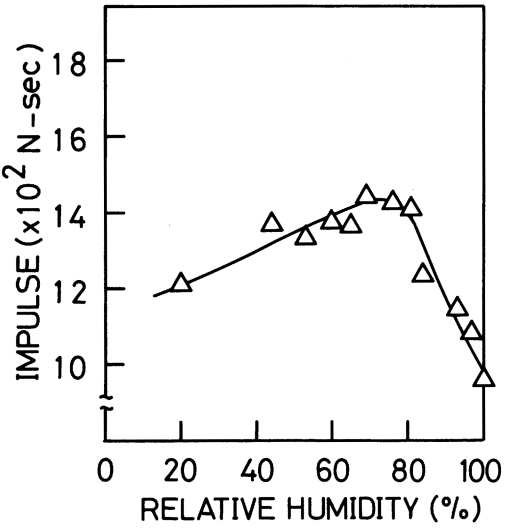

Fig. 7—Impulse *vs.* relative humidity curve of bleached softwood kraft pulp

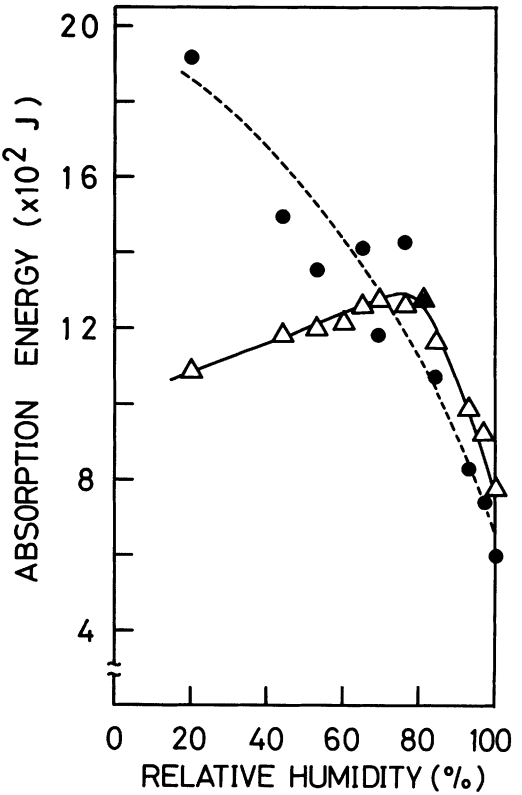

Fig. 8—Absorption energy *vs.* relative humidity curves of bleached softwood kraft pulp.
△ ——— △: under impact condition,
● - - - - ●: under static condition

The macroscopic structural changes of paper (i.e. destruction of interfibre bonding or deformation of single fibres) are the main factors in the static measurement. Above 80 per cent RH the drawing-out of fibres is, however, predominant during the deformation of the sheet in both cases as a result of decreases in the interfibre bonding force as shown in Figs. 3 to 6. Therefore, the abrupt decrease in the impulse or the absorption energy above 80 per cent RH may be due to the slippage between fibres described above.

In order to clarify the relation between molecular motion of cellulose and adsorbed water, kinetics on recrystallisation of amorphous cellulose under various relative humidities was studied using differential scanning calorimetry (DSC)—Kimura, Hatakeyama, Nakano,[6] x-ray diffraction method and

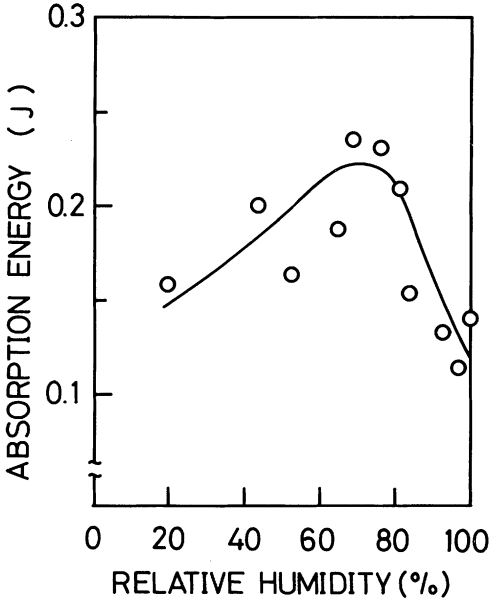

Fig. 9—Absorption energy *vs.* relative humidity curve of cellophane

torsional braid analysis (TBA)—Kimura, Hatakeyama, Yano, Kadoya.[7] From these studies, it is clear that recrystallisation occurred easily by conditioning at higher than 80 per cent RH. On the other hand, although the cellulose chain is not flexible enough to change its conformation in the range of 20–70 per cent RH, the cellulose molecule is able to move somewhat actively in a short range.

Fig. 10 shows the difference of specific scattering coefficient (S) between, before and after stress relaxation tests under various relative humidities. The curve shown in Fig. 10 has the minimum value at 70–80 per cent RH. In both the creep tests—Brezinski[8] it was also noted that a minimum in the percentage of creep recovery occurred between 70 and 80 per cent RH. In both impulse and static measurements, a boundary state is found in the range of 70–80 per cent RH as described above. From the results, it could be supposed that the manner in which water and cellulose interact varies at this point.

At least, above 80 per cent RH the slippage of fibres seems to be a dominant factor for the mechanism of deformation. Further studies are necessary for obtaining a thorough understanding of the behaviour of humidity dependence of paper under impact deformation.

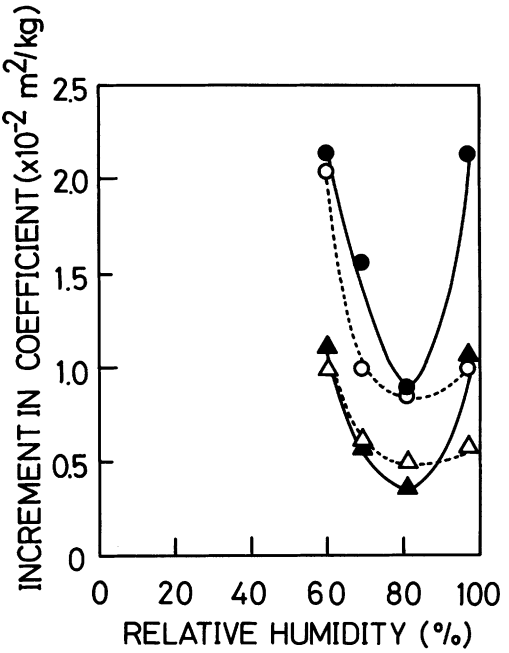

Fig. 10—Increase in specific scattering coefficient of stressed bleached softwood kraft pulp under various relative humidities

Duration of relaxation	*1 h*	*3 min*
Initial stress,		
80 per cent of failure load	●	○
60 per cent of failure load	▲	△

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Discussion

Mr B. Cornéer In your paper findings on the impact rupture on papers of various moisture content at 20° C are reported. For some types of paper, however, the impact strength properties at elevated temperatures are of great interest. My question therefore is whether you have any results of the impact rupture properties of paper at temperatures of up to 130° C (at different moisture contents). If such data are not available I would be grateful if you could speculate on what main changes on elevated temperature would bring to your results.

Kimura We have no such data at present, because it is impossible to carry out the measurements at an elevated temperature using this apparatus. In the field of wood chemistry, however, such an investigation is very important in connection with thermomechanical pulping. In adsorption isotherms for paper, the moisture contents changes with increasing temperature, therefore the results under elevated temperature conditions can not be compared simply with those at 20° C. I think that the behaviour of hydrogen bonds (intra and interfibrillar bonds) is much more affected by water than by heat. For this reason, I assume that the temperature effect on the rupture properties of paper is relatively small when compared at the same moisture content level. By the way, Salmén and Back have shown the influence of water on the glass transition temperature of cellulose. However, I do not know at present, although it would be very interesting, whether or not this type of molecular motion of cellulose influences mechanical rupture properties of paper.

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