LONGITUDINAL FLOW AND SAP DISPLACEMENT IN GREEN SAPWOOD STEMS

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ABSTRACT

End-grain pressure treatment of green softwood poles has been shown by previous workers to be improved by cutting away discs equal in thickness to the tracheid length. Xylem sap in the conducting sapwood of young trees which are felled for use as poles is under a hydrostatic tension and therefore retreats away from the cut surface and is replaced by air. In hardwoods with long xylem vessels this air forms a barrier to any solution forced in under pressure and is demonstrated to be very difficult to remove.

INTRODUCTION

The mechanism of liquid flow through wood in an axial direction has in the past been studied in two rather different ways. Firstly through small cubes or cylinders reduced to 2cm or 3cm in length, and secondly, and to a much lesser extent, through longer whole branches or poles.

Two principal applications have been made of these latter measurements. These are the calibrating of thermo-electric heat pulse devices to establish sap flow rates and whole tree transpiration (Swanson, 1965), and for investigating the practical problems associated with end grain penetration of waterborne preservatives into non-durable timbers. Hudson and Shelton (1969) point out the inapplicability of some of the mathematical analyses of flow to commercial preservative treatments and this is particularly true when longitudinal flow is considered. The reasons for this are varied but in general are connected with normal anatomical features and physiological processes associated with the water transport system of the living tree.

Failure to end penetrate a pole is usually attributed to a blocking of xylem vessels or tracheids by suspended particles of extraneous matter or by gas or air bubbles generated within the treating medium. Kelso *et al.* (1963) and Sucoff *et al.* (1965)

point out the need to use freshly prepared de-aerated water in order to obtain uniform rates of flow through small specimens for periods of a few hours.

Air blockage can, however, occur in another way, which is important particularly in the preparation and treatment of poles with preservative solutions. Sap contained in the xylem of standing trees is under a hydrostatic tension of up to about 20 atmospheres at the time of maximum tension which would normally correspond with the time of maximum transpiration during daylight hours. During the night and times of minimum transpiration this tension may fall to around 5 atmospheres (Scholander *et al.* 1965). Therefore, as soon as a cut is made into the conducting xylem, sap retreats from the cut surface both because of partial release of this tension and of continued transpiration through the leaves. Air is sucked in and will continue to be so until the air-water interface reaches a bordered pit in the tracheid or vessel end wall (Scholander *et al.,* 1957, Esau 1965). The amount of air sucked in and the length to which it extends upwards from the cut surface should be equivalent to the tracheid or vessel lengths of the particular species and tree as described by Mackay (1968).

In softwoods, Hudson and Shelton (1969) applied end pressure to force CCA preservative solutions through southern pine poles and found that if, after applying an initial pressure, they then cut off 1 in. from the end they could increase the flow rate by about 15 times with the same pressure. They explained these results by suggesting that the "wall" of air which has displaced the sap from the end tracheids of the softwood pole was removed by cutting off the disc. Liquid can then flow relatively unhindered through the series of full xylem tracheids.

Earlier work by the present author (1968) included an investigation of the effect of partial stem incising and air entry into conducting xylem of *Acer pseudoplatanus* on the overall transpiration of the whole plants. It was concluded that the effect of air entry into the sawn ends of hardwood poles could have a marked effect on sapwood penetration, hence this study was undertaken.

METHODS

The principal experimental material used was sapwood of *Eucalyptus rubida* and to a lesser extent for comparison only, *Pinus radiata.* Two sizes of material were used, young saplings 2m in length and up to 3cm in diameter, and pole sections up to 3m in length and 12cm in diameter. All specimens were chosen for uniform girth. After felling, all foliar material was removed as soon as possible and the cut basal and apical ends were sealed with lacquer. The poles were then stored sealed in polythene at 3°C. A minimum of six specimens of each species and size was tested in all experiments.

Normal experimental procedure was to determine the flow rate of freshly distilled water, initially through the whole specimen and then through successively shorter segments obtained by cutting off portions from either the efflux (apical) or influx (basal) end.

A constant pressure differential of 90cm water head (0.087 bar) was maintained across the small specimens, the issuing liquid was collected and weighed, and flux was determined on a volume per unit time basis. When the length is reduced and the pressure difference remains the same the pressure gradient along the remaining length therefore increases and the flow rate increases. By dividing through by a factor, l_0/l_1, where l_1 and l_0 are respectively the present and initial lengths, then the pressure gradient is maintained constant and the adjusted values of the flux are those which would be obtained under conditions of constant pressure gradient.

A pressure end cap (Dale, 1969), Fig. 1, was fitted to the larger poles and a pressure of 1.36 bar applied through a reservoir containing the distilled water. The effluent was collected and weighted at regular intervals.

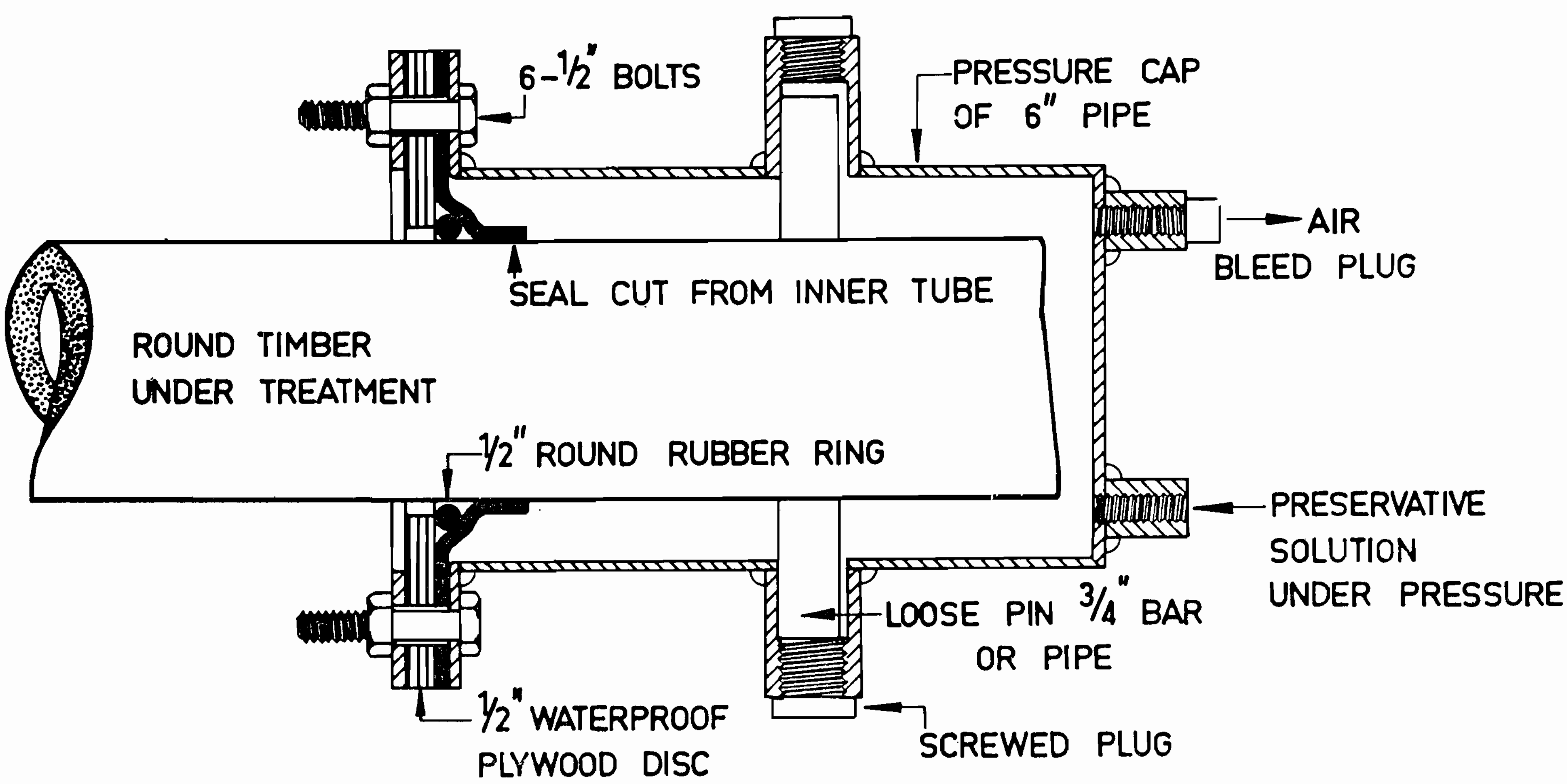

FIG. 1—Cross-section of pressure cap (Dale 1969).

All cut surfaces of the small diameter specimens were trimmed with a sharp blade and those of the poles were planed after sawing.

RESULTS AND DISCUSSIONS

In a study such as this where flow rates were measured successively on the same specimen (or part of it), it was important to establish that a constant flow rate would have persisted in the intact specimen over a period of time equivalent to the duration of the subsequent experiments. Using the techniques described above, flow rates as shown in Fig. 2 were obtained for the two species.

E. rubida gave constant results over a period of 4 hours, but initially *P. radiata* did

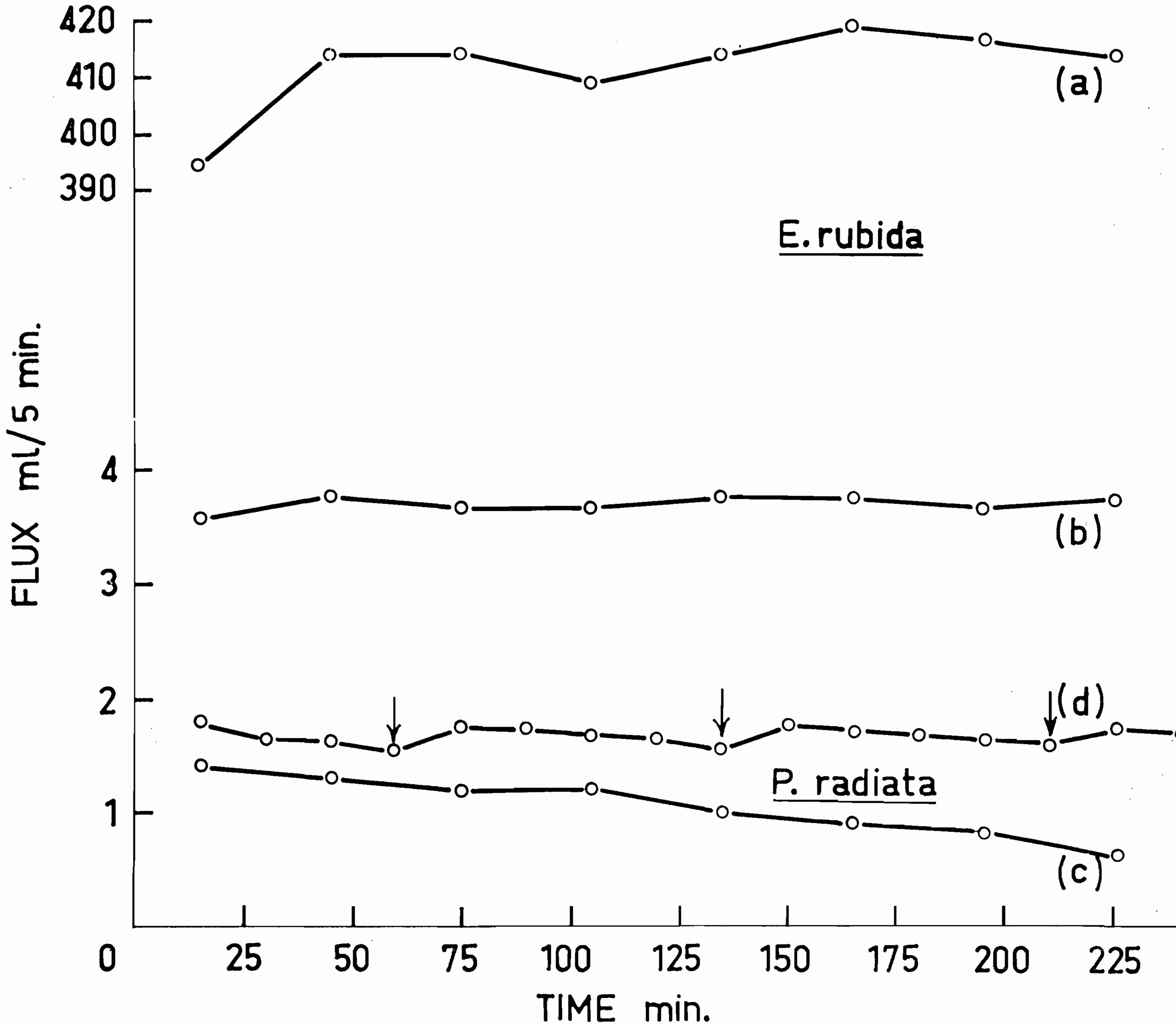

FIG. 2—Flux over a 4-hr period through **E. rubida** pole (a) and small specimen (b), and **P. radiata** small specimens with (d) and without (c) end slicing as denoted by arrows.

not (Fig. 2c). The reason for this was that bleeding of resin from the efflux end of the specimen spread over and significantly reduced the surface area of the cut face and thus impeded water flow. To overcome this a very thin slice was removed regularly and Fig. 2d shows typical results obtained. However, a certain amount of bleeding from the influx end caused a similar effect although to a much lesser extent. To remove wood from the influx end would have interfered with the necessary conditions of the treatments, hence *P. radiata* experiments were conducted over a shorter period of time with a maximum of 30min.

The effect of reducing the length of the conducting cylinder of small specimens of *E. rubida* by cutting from the efflux end is shown in Fig. 3a. The important point is that the flux, through the shorter lengths in particular, increases. However, according to the Darcy equation, under conditions of constant pressure gradient through a cylinder of constant bore the flux should remain constant independent of length. Larger poles of this species show a similar effect as shown in Fig. 3b.

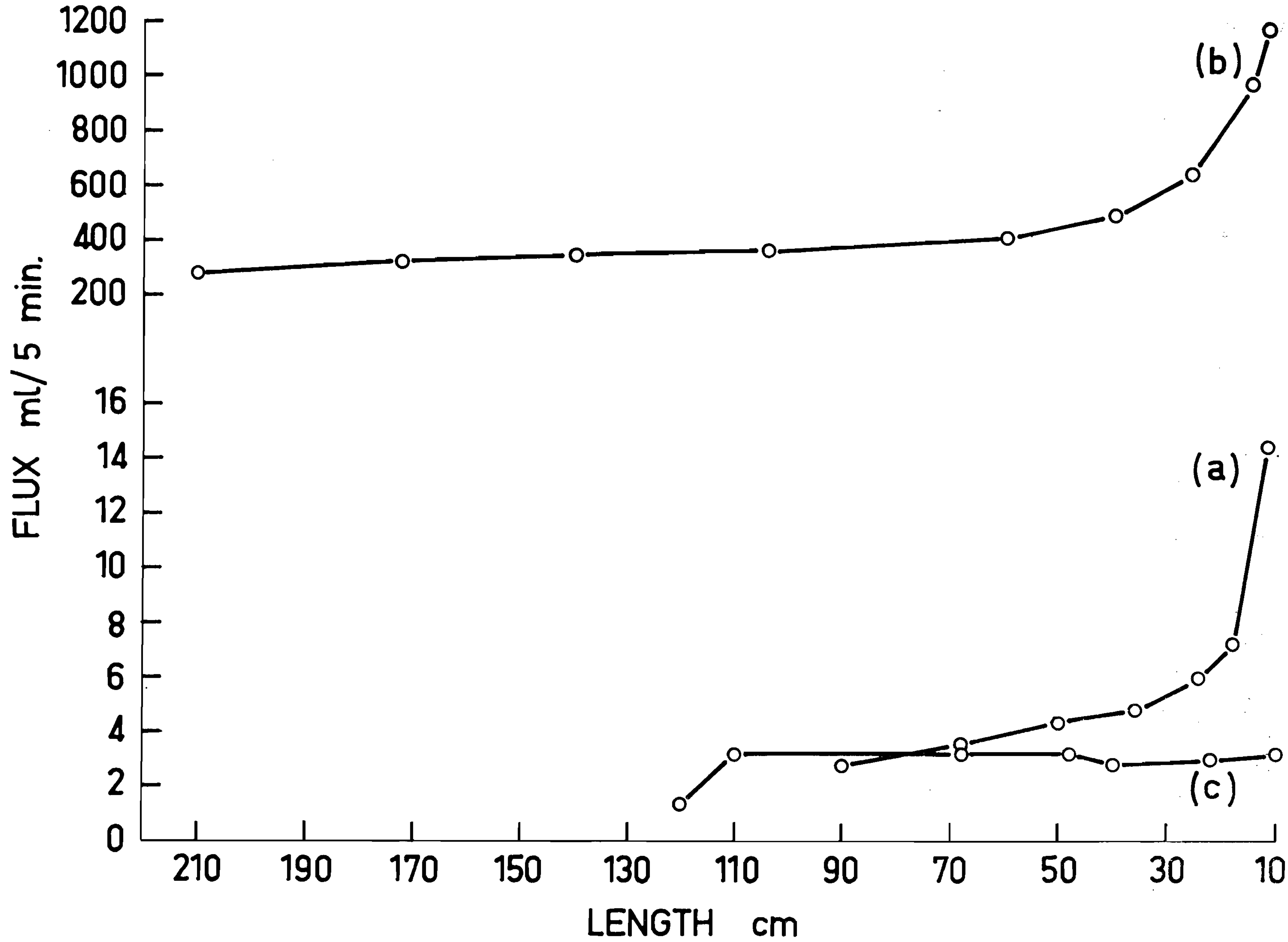

FIG 3—Flux through **E. rubida** stems after adjustment for increased pressure gradient; (a) sapling, portions removed from efflux end, (b) pole, portions removed from efflux end, (c) sapling, portions removed from influx end.

Reducing the length by cutting from the influx end also shows a pattern of results which are similar in both small specimens and large poles. Fig. 3c shows a typical result for a small specimen. It should be noted that the increasing flux through shorter lengths is now absent and is replaced by an initial increase at the first cuts followed by more constant rates.

It can be concluded here that air is located in the cut vessels at the basal end of each pole. It has been shown that the median vessel length in diffuse porous hardwoods is considerably less than the mean (Mackay, 1968; Skene and Balodis, 1968), and in eucalypt species is probably less than 20cm. Thus, when reducing the length of the pole by cutting from the efflux end the greatest increase in flux is obtained only with the final cut when the length remaining is similar to or less than the median vessel length. Only then does flow of water under pressure occur through most of the available vessels in the xylem sapwood cylinder. Conversely, when cutting from the influx end, most of the air-blocked vessels are cleared by the first and second cuts and only at these points can an increase in flux be expected.

To demonstrate the validity of these conclusions, in a few poles air pressure was applied to the efflux end while the influx end was held under water. Air could be seen emerging from the cut end for a few seconds and subsequent flow rates at this length were then increased (Fig. 4). Because of the high negative hydrostatic pressure in the vessels relative to the low air pressure applied ($88 g/cm^2$ ($20 lb/in^2$)) it is probable that the air which was expelled was from only the basal few millimetres and thus only a small number of vessels are likely to have been reopened for liquid flow.

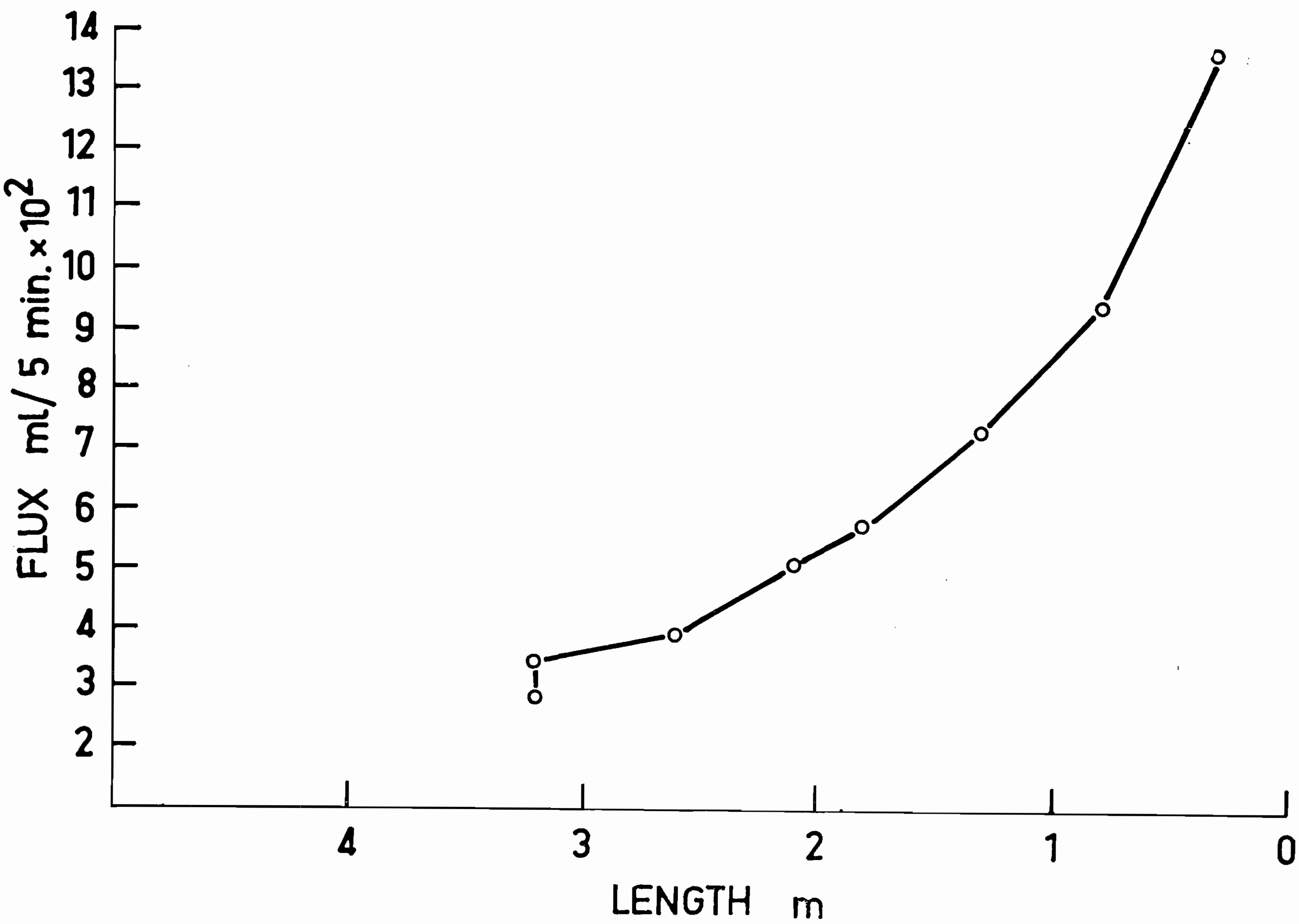

FIG. 4—Flux through **E. rubida** pole section to which an initial pressure was applied to the efflux end before portions removed from this end.

In *P. radiata* a similar pattern of results was obtained when cuts were made from the influx end. However, these cuts were only 1mm in length initially and therefore the effect of entrapped air in the basal tracheids is removed with only a short reduction in length. These results (Table 1) are to be expected because of the known short

TABLE 1—Flux through **P. radiata** small specimen portions removed from the influx end

Portions Removed No.	Length (cm)	Adjusted Flux (ml/5 min.)
1	0.1	2.8
2	0.1	4.9
3	0.1	7.3
4	1.0	10.6
5	1.0	10.2
6	10.0	11.5
7	10.0	11.1

lengths of *P. radiata* tracheids (4mm to 5mm), and are in accordance with the findings of Hudson and Shelton (1969).

It is therefore unlikely that the cutting of thin slices from the basal end of hardwood poles, as is recommended for softwood poles, which are being pressure end-treated will significantly increase flow rate. The extent to which air, introduced by the relief of negative hydrostatic pressures, causes a blocking action is related to the length of the individual vessels or tracheids of any given species. It is for this reason that such a treatment would be most effective in softwoods and least effective in hardwoods, particularly those ring porous species which are said to contain very long vessels (Preston 1952). Removal of entrapped air could probably best be carried out in hardwood poles by applying a high positive pressure to the apical cut end while the basal end is held below the surface of the treating liquid. Provided the pressure applied equalled or exceeded the residual hydrostatic tension in the xylem cylinder at the time of treatment, then continuity of liquid channels would be re-established and air would no longer be a barrier to flow.

REFERENCES

DALE, F. A. 1969: Sap displacement simplified. **CSIRO Forest Products Newsletter 360.**

ESAU, K. 1965: "Plant Anatomy". John Wiley & Sons, New York, London, Sydney.

HUDSON, M. S., and SHELTON, S. V. 1969: Longitudinal flow of liquids in southern pine poles. **Forest Products Journal 19 (5):** 25.

KELSO, W. C.; GERTJEJENSEN, R. D., and HOSSFIELD, R. L. 1963: The effect of air blockage upon the permeability of wood to liquids. **University of Minnesota Agriculture Equipment Station Technical Bulletin 242.**

MACKAY, J. F. G. 1968: The state and movement of water in the stems of woody plants. (Ph.D. Thesis lodged in the University of Aberdeen library, UK).

PRESTON, R. D. 1952: Water movement along the stems of trees. Pp 265-321 in "Deformation and flow in biological systems". (A. Frey-Wyssling, Ed.) North Holland Publishing Co., Amsterdam.

SCHOLANDER, P. F.; HAMMEL, H. T.; BRADSTRET, E. D., and HEMMINGSEN, E. A. 1965: Sap pressure in vascular plants. **Science 148:** 339.

SCHOLANDER, P. F.; RUDD, B., and LEIVESTAD, H. 1957: The rise of sap in a tropical liana. **Plant Physiology 32 (1):** 1.

SKENE, D. S., and BALODIS, V. 1968: A study of vessel length in **Eucalyptus obliqua. Journal of Experimental Botany 19 (61):** 825.

SUCOFF, E. I.; CHEN, P. Y. S., and HOSSFELD, R. L. 1965: Permeability of unseasoned xylem of northern white cedar. **Forest Products Journal 15 (8):** 321.

SWANSON, R. W. 1965: Seasonal course of transpiration of lodgepole pine and engelmann spruce. Appendix 1. **Proceedings of the International Symposium on Forest Hydrology, Pennsylvania State University.**