Mobile Shields for Standard Woodworking Machinery as an Element of a Protection and Accident Prevention System – The Idea and Testing

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Mobile shields at woodworking machine workstations were considered in this work as part of a protection and accident prevention system. A shield design based on an aluminium frame is proposed. The results of the experimental tests demonstrated the high efficiency of material kick attenuation using the mobile shields, irrespective of their position and the filling used. Operational tests on the mobile shields were performed in a woodworking shop, which confirmed their usefulness and made it possible to supplement the conclusions with interesting observations concerning their dimensional and visual features, among other things.

Keywords: Guarding; Kickback; Woodworking; Protection; Accident prevention; Ricochet

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INTRODUCTION

The separation of protection elements (most often in the form of protective fencing) is used in many industries and fulfils a series of essential functions, such as preventing unauthorized persons from approaching and accessing machinery and excluding the presence of personnel (except for precisely defined cases) in zones that are classified as particularly dangerous (*e.g.*, within the direct reach of a robot). Fences can also be used as partitions between workstations or to separate them from internal transportation routes and storage areas. The primary purpose of this form of protection is to organize the area of a manufacturing hall by setting clear boundaries that are difficult to cross. In the above cases, special care is taken to ensure that the fence is sufficiently effective at discouraging unauthorized access. For example, a fence must prevent unauthorized access under it (item 4.3 in ISO 13857 (2008)) and it cannot be too low (item 4.2.2 in ISO 13857 (2008)). Furthermore, the fence design should not facilitate climbing, such as on protruding elements (item 5.18 in ISO 14120 (2015)). An average woodworking shop or small furniture factory usually does not have a large manufacturing hall, does not use robotic workstations, and employs a few reliable workers, and therefore the protections mentioned above are often not considered to be of key importance because there is no need for such restrictive access control. In such cases, it is not necessary to use less or more complicated modular fencing systems that are anchored permanently to the floor. This does not mean though that it is not necessary to use any separating protection elements in these cases. The operation of woodworking machinery used in these types of companies poses a specific hazard that cannot be overlooked because kickback of a work piece happens too quickly to react to it, even too fast to see it (Anthony 2014).

Although woodworking machine operators are exposed to a considerable number of harmful factors (Kvietková *et al*. 2015; Rogoziński *et al*. 2015; Ratnasingam *et al*. 2016), it is widely known that the mechanical processing of wood or wood-based materials using circular sawing machines, planing machines, and spindle moulders can involve a dangerous phenomenon called workpiece kickback (OSHA 3157 1999; HSE 2014; Dąbrowski and Górski 2018). Kickback is an uncontrolled rapid movement of a workpiece or part of it in an improper direction (*e.g.*, opposite to the feed direction), which causes a direct hazard to the operator and other persons (or machines) in the vicinity. One of the representative surveys of table/bench saw injuries showed that the workpiece kickback was the source of the problem in about 40 percent of the cases (Chowdhury and Paul 2011). Woodworking machinery is classified as hazardous, and in Annex I, item 2.3 of EC Directive 2006/42/EC (2006) it is stated that 'where the machinery is likely to be used in conditions involving the risk of ejection of workpieces or parts of them, it must be designed, constructed, or equipped in such a way as to prevent such ejection, or, if this is not possible, so that the ejection does not engender risks for the operator and/or exposed persons'. Unfortunately, the phenomenon of kickback has not yet been eliminated, although attempts have been made to do so. For example, in the 1980s, the French INRS developed and tested a circular sawing machine model that posed no risk of kickback. However, for technological reasons, the sawing machine could not be used because the quality of the cut material was unacceptable. In practice, current activities that are aimed at reducing the risk of kickback involve the appropriate training of joiners or woodworking machine operators (stressing the importance of always being in a safe place, meaning out of the path of kickback) and the use of technical risk-reduction methods. One such method could be the use of mobile shields for woodworking machinery, as is described in this study. Protective shields of this type should not be the same as standard fencing modules designed solely to prevent people from accessing a specific zone. The design should not consider whether a person can get under them, but rather how they behave in a collision with a rapidly kicked-back workpiece, which is characteristic of the woodworking industry. These shields should mainly limit the danger zone and protect other workers, but also protect the operator from external hazards.

The aim of this study was to present the idea of using mobile shields as an element of a protection and accident prevention system, and to examine the protective features and suitability of these shields for standard woodworking machinery. This study further verified the results of impact tests of the mobile protective shields carried out in a laboratory and exploitation tests of these shields in a regular woodworking shop, as described in detail below.

Idea and Details of the Shield Construction

A shield that is placed close to a machine on a kickback path should absorb all of the impact energy to protect the people behind it (against death or serious injury) or objects (against damage). An analysis of current commercial products demonstrated that only a few of them could be adopted as mobile shields for woodworking machinery. Eventually, it was decided to design shields based on a frame structure with 40-mm × 40-mm aluminium profiles.

The design of the protective shield is shown in Fig. 1. The shield can be freely moved around a manufacturing hall on four wheels with a lock and was placed on two 80-cm long skids to ensure suitable stability. Mobility was deemed a necessary condition in terms of the expectations of potential users. Small woodworking shops and furniture factories maintain their positions in the market chiefly because of flexibility in manufacturing, which may necessitate frequent organizational changes at workstations and in manufacturing halls.

The following factors were considered when selecting the fillings of the shield frames:

- Materials recommended in standards regarding the design of shields for woodworking machines (*e.g.*, steel, aluminium, and polycarbonate) were preferred;
- The testers searched for fillings with a diverse structure (*e.g.*, solid *versus* mesh, and transparent *versus* opaque).

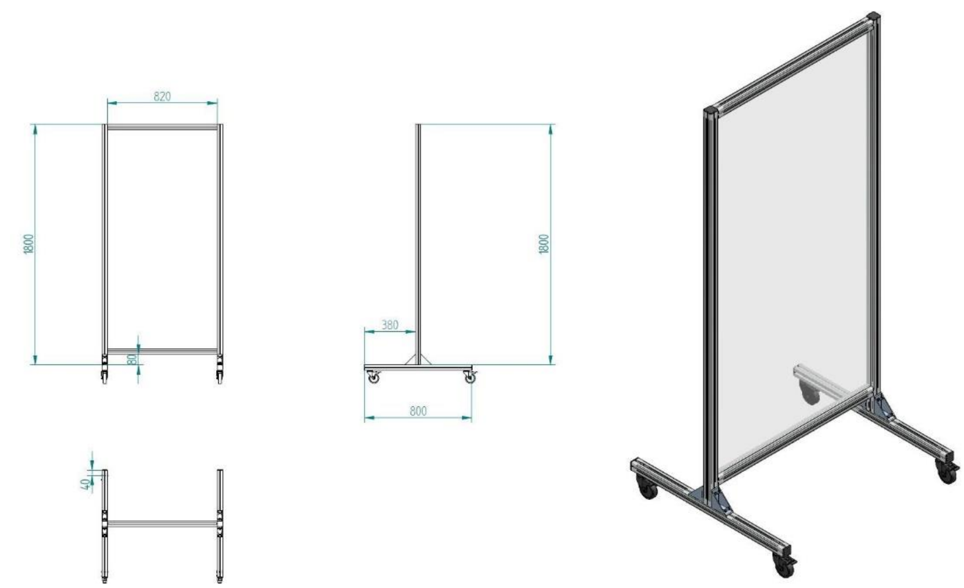


Fig. 1. General view of the shields designed at the CIOP-PIB. All dimensions were in mm

As a result, the following four filling types were selected:

- 5-mm thick aluminium sheets;
- Corrugated welded steel mesh with the dimensions 40 mm × 40 mm and made of Φ3-mm wire;
- 5-mm thick transparent polycarbonate sheets;
- Chain link net with the dimensions 5 mm × 5 mm and made of Φ1-mm steel wire.

When the above filling types were selected, the testers also considered the following options, but rejected them:

- Strip curtains (made of soft polyvinyl chloride or polyurethane) used successfully in woodworking machinery (Pavlovic and Fragassa 2016)
- Sports mesh (made of polypropylene) used to construct fencing around sports grounds,
- Chain mail made of steel links, currently used primarily in gloves and aprons for butchers.

The first two options were regarded as too weak, and the third one was too expensive.

EXPERIMENTAL

The tests were divided into two stages. The first stage involved laboratory tests to experimentally determine (in strictly controlled conditions) the impact of the shield design features on their efficiency in preventing accidents at work. In this stage, the testers compared the effectiveness of stationary (designed as rigid frames fixed to the floor) and mobile structures (frames on four wheels with a brake). The tests were performed at the CIOP-PIB laboratories. The second stage involved operational tests that enabled practical testing of the functionality of different variants of the mobile shields in the conditions of a normally operating and well-organized woodworking shop. The tests were performed in the woodworking shop of the Faculty of Wood Technology of the Warsaw University of Life Sciences.

In the search for test methods for Stage 1, attempts were initially made to use the latest editions of technical standards (annex B and C in ISO 14120 (2015); annex D in ISO 19085-1 (2017)) concerning the methods of dynamic testing of machine tool shields regarding exposure to anticipated mechanical impacts. However, it appeared that these methods omitted two important issues in the case of mobile shields separating workstations. The first issue concerned a risk related to a workpiece rebounding off the inner surface of the shield and ricocheting to a worker standing nearby (Zukas and Gaskill 1996). The second issue pertained to the necessity of testing the stability of a mobile structure. For these reasons, an original test method was developed to remedy these deficiencies. The main purpose of this method was to assess the characteristics of the shield used, such as attenuation (absorption) of the impact energy and stability.

The test stand consisted of a vertical spindle milling machine (Fig. 2) on a table where a special pneumatic-mechanical assembly was mounted. The function of the assembly was to press a workpiece to the milling machine guides and table, and initiate kickback during milling (Dąbrowski and Górski 2018). The test stand used for the kickback tests was based on EN 847-1 (1997). Originally, it was to be used to certify tools for hand-fed milling machines according to the German standard BGR 500 (2008). The BG-TEST marking on tools for woodworking means that they passed this special kickback test. The test stand was adapted for samples nominally measuring 18 mm × 40 mm × 500 mm and weighing 230 g. The tested shields were placed in the kickback path at identical distances (1.5 m) from the machine tool. The shields were set up as mobile shields rather than being fixed to the floor as stationary shields, where the wheels would be locked with a brake. The kickback speed (speed of a workpiece on exiting the milling machine table) was measured using a Fastec InLine 1000 high speed camera (San Diego, USA) at 250 frames/s, whereas the course of the collision between the workpiece and shield was recorded with a Photron Fastcam SA1.1 camera (Tokyo, Japan) at 2000 frames/s.

The kinematic and dynamic analysis of the collision was performed using TEMA Motion software (Version 4.0, Image Systems AB, Linköping, Sweden). This software helped to determine the sample speed before and after collision with the shield, angular deflection of the shield, and linear displacement of the shield.

The data above were used to specify the contact time, *i.e.*, the time when the sample was in contact with a shield during collision, and calculate the attenuation (absorption) of energy, which was called the damping factor. This was calculated using Eq. 1,

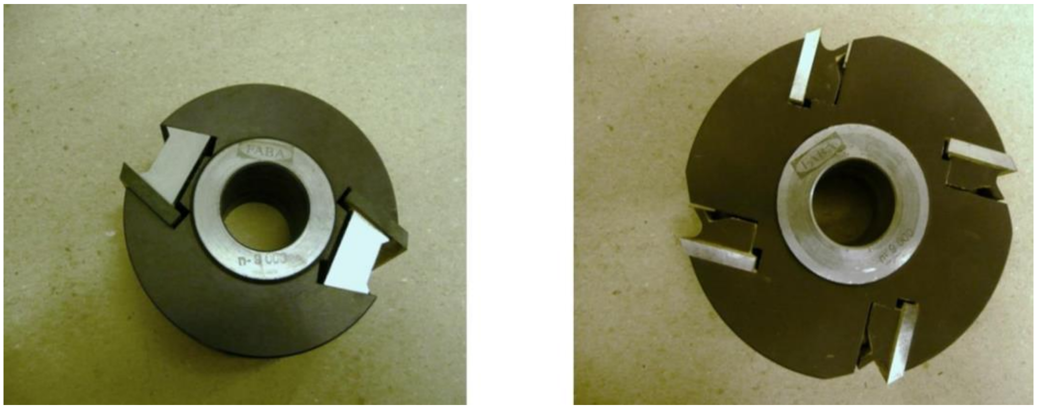
$$\textit{Damping Factor} = [(E_{k1} - E_{k2}) / E_{k1}] \times 100\% \quad (1)$$

where E_{k1} is the kinetic energy (J) of the sample before collision, and E_{k2} is the kinetic energy (J) of the sample immediately after collision.

Fig. 2. General view of the test stand - woodworking machine with accessories and the tested shield

The damping factor was found to be the most suitable for assessment of the protective characteristics of the tested objects because of the risk of ricochet. Additionally, the approximate ricochet range, *i.e.*, the distance at which the sample was kicked off the shield, was estimated.

The laboratory tests began with preliminary tests that were performed to determine the influences of the machine type, workpiece material, and cutting speed on the kickback speed. The purpose of the tests was to obtain data that would help to adequately define the experimental procedure to be used in subsequent testing of the shields. At the preliminary test stage, the testers used two different cutterheads (FABA 3300 and FABA 1100) that were produced by FABA (Baboszewo, Poland) and designed for a hand-fed milling machine. The cutterheads are shown in Fig. 3. The samples were made of three different materials (medium-density fibreboard (MDF), pine wood, and chipboard) and the cutting speed ranged from 17 m/s to 59 m/s. Based on the results of these tests, it was decided that the FABA 1100 4-knife cutterhead, chipboard samples, and cutting speed of 40 m/s would be used in the main tests. These cutting conditions were selected to obtain the highest kickback energy possible and maintain real conditions in which typical hand-fed woodworking occurs.



(a) (b)

Fig. 3. Tools used in the preliminary tests: (a) 2-knife cutterhead (FABA 3300) and (b) 4-knife cutterhead (FABA 1100)

A series of workstations with standard woodworking machinery, located in three halls of a regular woodworking shop, were selected for operational testing of the shields. The machinery included a thickness planing machine, a surface planing machine, a single spindle vertical moulding machine, a disk sander, a wide-belt sanding machine, and a circular sawing machine. After the test stands were selected, mobile shields were placed on them. Various aspects of the functional and operational characteristics were tested on these workstations for more than 10 d with the active participation of people performing tasks and regular users of the machines, including a qualified master joiner. Then, all of the people involved in this project developed separate reports that were subjected to further analysis.

RESULTS AND DISCUSSION

At the beginning of the experiment, the testers checked which of the two cutterheads (2-knife or 4-knife) posed the greatest hazard if kickback were to occur. In the comparative test, the testers used an MDF sample. The test results are shown in Fig. 4. The difference between the cutterheads was not too major; however, (regardless of the cutting speed) the 4-knife cutterhead caused a slightly higher kickback speed. For this reason, only this tool was used in all of the subsequent tests. The first test involved determining the effect of the workpiece material (MDF, pine wood, and chipboard) and cutting speed (17 m/s to 59 m/s) on the kickback speed (Fig. 5). It was found that the effect of both factors was negligible. In virtually all of the cases (except for the pine wood samples), the average kickback speed was slightly above 10 m/s. For this reason, in all of the subsequent tests, the testers used samples made of chipboard and a cutting speed of 40 m/s, which is the value typically recommended by the tool producer. The projection of the blades from the cutterhead body was 1.1 mm, which was in accordance with the requirements for hand-fed machines.

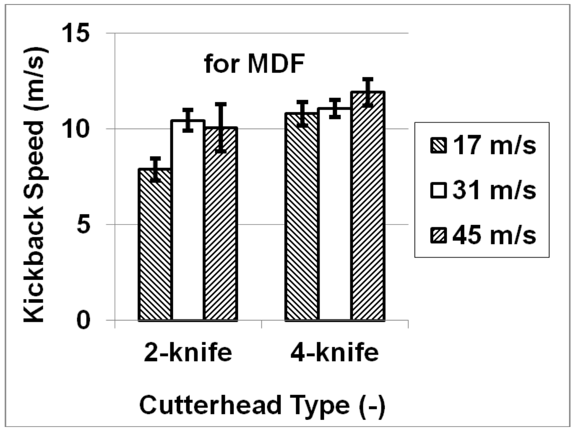


Fig. 4. Effect of the cutterhead type and cutting speed on the kickback speed in the case of MDF sample milling

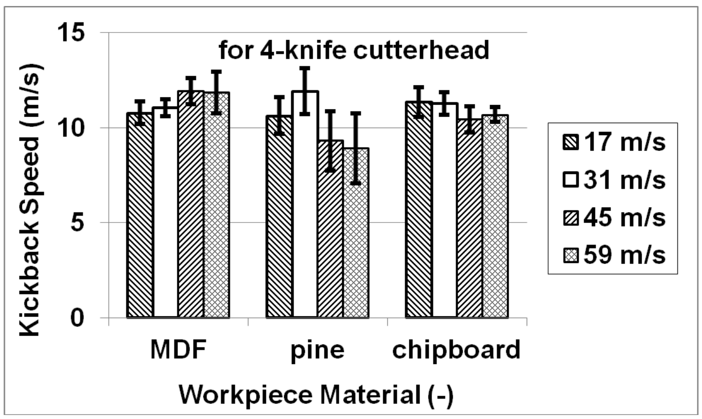


Fig. 5. Effect of the workpiece material and cutting speed on the kickback speed for milling with a 4-knife cutterhead

The main part of the laboratory tests included comparative tests of the shields with the four filling types (aluminium, chain link net, polycarbonate, and corrugated steel mesh). Detailed results of the comparative tests were selected and are shown in Figs. 6, 7, and 8, which show that all of the tested shields were characterized by a relatively high damping factor. The best result (97%) was obtained by the aluminium filling and the worst (87%) by the steel net (Fig. 6). The steel net was found to be the most elastic. This was indicated by a noticeably longer contact time with the rebounded samples, which was approximately five times longer than the contact time for the aluminium sheet filling, as is shown in Fig. 8. Additionally, all of the shields were characterized by an acceptably minor ricochet range. Again, the best result (0.8 m) was obtained by the aluminium filling and the worst (1.0 m) by the steel net (Fig. 7). This reflected the practical consequences of the different levels of damping factors for both shields.

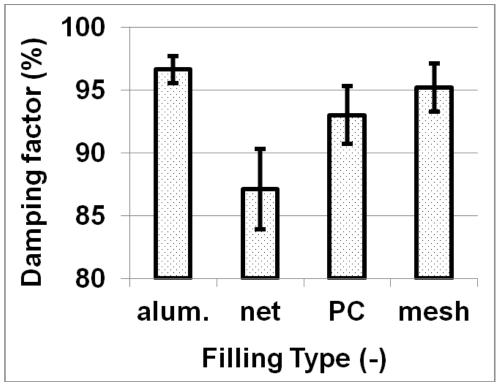


Fig. 6. Effect of the filling type on the damping factor; alum. – aluminium; and PC – polycarbonate

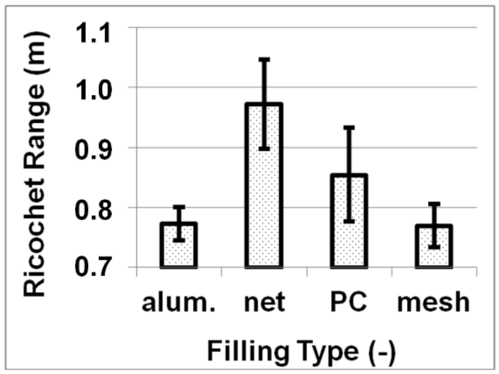


Fig. 7. Effect of the filling type on the ricochet range

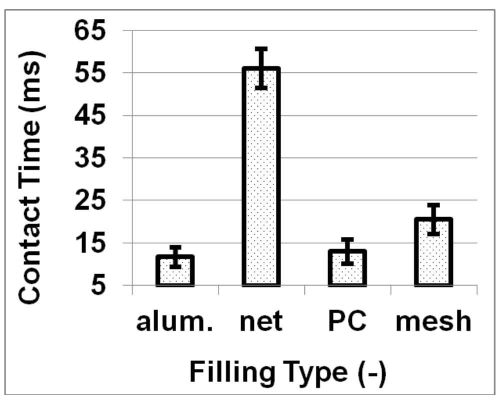


Fig. 8. Effect of the filling type on the contact time

A series of positive conclusions were reached based on the test results. All of the shields (regardless of the filling type) were found to be sufficiently stable and resistant to impact. None of them showed any signs of puncturing, permanent deformation, or damage. All of the filling types (regardless of certain differences between them) can be considered useful in practice. The mobile shields (placed on locked wheels) did not change their positions as a result of impacts caused by the kickback of a workpiece, even though the impact energy was three times greater than the one applied during the impact test of the shields, in accordance with the basic standard for woodworking machinery (ISO 19085-1 2017).

All four types of mobile shields were qualified to be included in the operational tests performed under the prevailing conditions of a normally operating and well-organized woodworking shop. A final report drawn up by the woodworking shop workers upon completion of this test stage described the following issues regarding the practical functionality of the shields. The testers brought attention to the fact that although the main advantage of the tested shields was the reduction of a kickback hazard zone, an equally important function performed by the shields was the demarcation of the space where only a machine operator should be present. This also reduced the risk of an accident because of an operator being knocked down by another person (for example, someone behind the operator) (Fig. 9).

Fig. 9. A shield separates two workstations, which limited the kickback hazard zone and reduced the risk of the operator being knocked down by another worker

It was proposed that the dimensions of the shield, particularly its height, depend on the type of woodworking machine. In the case of circular sawing machines, the height of the shields should be at least 2.2 m. This value was proposed based on the wall trace of a workpiece that was cut on a standard circular sawing machine and struck a wall (Fig. 10). This postulate is difficult to overlook considering the information from court trials following fatal injuries to the neck, which took place in Poland as a result of kickback from multi-blade circular sawing machines and two-saw edgers. A sample that is sawn on a circular sawing machine can be ejected diagonally upwards and fly over a shield that is too short. For other workstations in the woodworking shop, a height of 1.3 m was found to be suitable, whereas the width of the tested shields was considered optimal in terms of their mobility. It was decided that if more width was necessary, two shields could be placed next to each other (Fig. 10).

The transparency of the shields, which determines the possibility of observing the workstation, was found to be a particularly essential practical problem. Lack of eye contact with the operator not only impedes regular communication, but may also delay the provision of aid in the event of an accident. For this reason, the use of shields lower than human eye level should be recommended in all cases where such height is sufficient. In these cases, the filling type was unimportant. This was not the case with taller shields. In the case of the aluminium sheet shield, the lack of any visibility was found to be a disqualifying shortcoming. In the case of the shield with a mesh filling made of 3-mm wire with a mesh size of 40 mm × 40 mm, the visibility was better, but still insufficient. The best results were achieved by the shield made of fine net (1-mm wire with a net mesh size of 5 mm × 5 mm). The polycarbonate sheet was the most transparent, but this feature made it almost invisible, which led to accidental collisions. In this case, it would be necessary to affix special warning signs.

Fig. 10. A woodworking shop worker demonstrates, based on his personal experience, a suitable height in his opinion for shields protecting against kickback from a circular sawing machine; two shields were placed next to each other to increase the width of the separated zone

Fig. 11. The design of the shields saved space during their transportation and storage

High ratings were given for the structural stability of the shields when the wheels were locked, their manoeuvrability, and the possibility of storage in small areas (Fig. 11).

CONCLUSIONS

1. All of the mobile shields that were placed on locked wheels were found to be as effective as stationary shields. Fixing the shields to the floor was not found to be beneficial.
2. The risk related to ricochet (when a workpiece rebounds off of a shield) appeared to be minor. All of the tested filling types demonstrated a sufficiently high capability at attenuating the impact energy. The highest damping factor (97%) and lowest ricochet range (approximately 0.8 m) were obtained with the aluminium filling. The lowest results for these factors were obtained with the steel net (87% and approximately 1.0 m, respectively).
3. The main advantages of the mobile shields included the reduction of kickback hazard zones and clear demarcation of the space in which only the machine operator should be present. This made it possible to limit the risk of accidents resulting from an operator being knocked down by another worker. In this way, mobile shields can be an element of a protection and accident prevention system.
4. It was determined that the height of a shield should depend on the type of woodworking machine. In the case of circular sawing machines, this height should be at least 2.2 m. In the case of other standard woodworking machinery, a height of 1.3 m should be sufficient.
5. Shields should allow eye contact with the machine operator. For this reason, the use of shields lower than human eye level are recommended in all cases where such height is sufficient. For taller shields, a sufficiently transparent filling was determined to be necessary.

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