THE SAXO TURBINE – AN INTERESTING SELECTION FOR RELIABLE AND EFFICIENT OPERATION

Janez Gale*, Damir Dolenc**, Anton Bergant†, Sandi Cizelj‡

Double-regulated vertical axial water turbine with conical distributor, which is worldwide known as a Saxo-type turbine, is the main subject of this paper. Due to continuous research, development and improvement, advanced and compact structure, simplified civil construction works, reliability, ecological design and versatile applicability, the turbine became very recognizable product of company Litostroj Power, with over 30 successfully commissioned units in North American and Canadian market mainly. Authors see the Saxo turbine as one of the most interesting and suitable solutions for small and medium size hydro power plants. This paper aims to draw attention on this unique and interesting turbine design especially because experiences show that hydro power plant investors are somehow conservative and they mainly prefer and trust in more conventional turbine types i.e. Kaplan turbines and tubular turbines. The paper enlightens important design, hydraulic, economic and operation advantages of the Saxo-type turbines and points out most obvious advantages comparing to tubular and Kaplan type turbines. As an evidence of safe and reliable operation, there is a special section at the end of the paper which is focused on field-feedback experiences obtained during extensive turbine testing at commissioning tests, final field performance acceptance tests and operation experiences.

Keywords: *vertical axial water turbine, Saxo turbine, operation feedback, medium size HPP, double-regulated turbine*

1. Introduction

The Saxo turbine is a double-regulated, vertical axial water turbine with construction that is at first glance similar to the upstream S-type turbine according to the IEC 61364 code [1], however, with vertical shaft arrangement and corresponding intake and draft tube elbow and with a conical semi-axial guide vane apparatus (see also Fig. 1). One can say that the Saxo turbine is similar to the tubular turbine in the section between the inlet elbow and the guide vanes, while in the section between the runner and the draft tube exit, it is similar to the Kaplan turbine. Due to its compact construction, the Saxo turbine is applicable for net heads up to 35 m, discharges up to 85 m^3/s and turbine output power up to 20 MW. Figure 2 shows a scheme of typical operational ranges of tubular, Kaplan and Saxo turbines with approximate number of runner blades and runner diameter for Saxo turbines. The Saxo turbine partially covers the operating ranges of both, the Kaplan and tubular turbines.

The Litostroj Power company has a lot of manufacturing and operational experiences with Saxo turbines, as it is already successfully commissioned over 30 units during the pre-

* J. Gale, PhD, R&D Department, Research Centre ZEL-EN d.o.o., Slovenia
** D. Dolenc, MSc, Commissioning Department, Litostroj Power d.o.o., Slovenia
† A. Bergant, PhD, R&D Department, Litostroj Power d.o.o., Slovenia
‡ S. Cizelj, MSc, R&D Division, Litostroj Power d.o.o., Slovenia

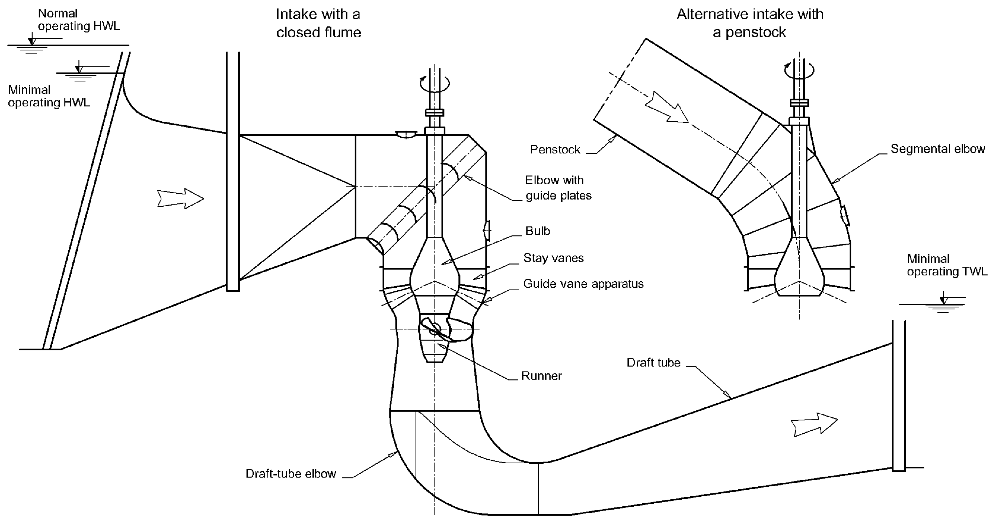

Fig.1: Typical cross-section of the Saxo turbine (water passage)

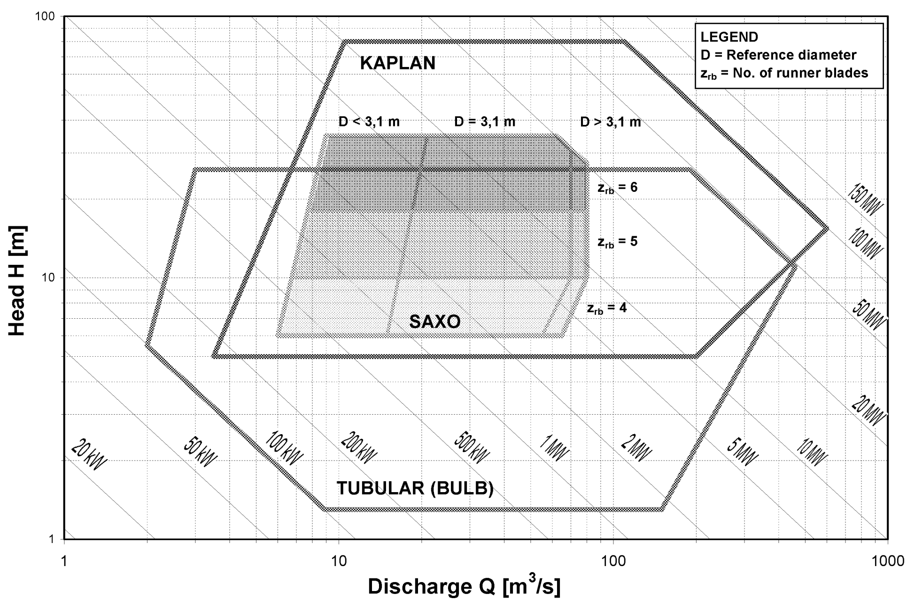

Fig.2: Typical operation range of the Saxo, Kaplan and tubular turbines

vious two decades (see Table 1). Experiences show that investors of hydropower plants prefer to choose Kaplan turbines with a vertical shaft, primarily because of their advantages during operation (reliability, maintenance, double-regulation, etc,), and possibilities of easily installing generators with large rotating masses. Investors also prefer tubular turbines with horizontal shafts because of simplified civil construction works and relatively good hydraulic design. The Saxo turbine, due to its compact design and vertical arrangement contains and even exceeds operational and maintenance characteristics of Kaplan turbines and has a better hydraulic design (energetic performance) than tubular turbines. The Saxo turbines have fewer problems with handling and installation of the equipment due to smaller components, which allows utilization of a smaller powerhouse crane, and consequently less bulky powerhouse structure and quicker installation of factory pre-assembled components. At the Pouvoir Riverin HPP for example, the inlet elbow, stay and guide vanes with regulating mechanism were preassembled in the workshop and were transported and concreted as a one single piece.

HPP Project	H_n [m]	Q [m^3/s]	P [MW]	n [min^{-1}]	No. of units	Year of supply	Owner
Sainte-Anne	24	25	5.38	300	1	1996	Axor Group, Inc
Jean Guerin	24	27.85	5.78	300	1	1997	Axor Group, Inc
Pouvoir Riverin	28	8	2.01	600	1	1999	Algonquin Power Fund, Inc
Sainte-Anne II	24	25	5.38	300	1	2002	Société d'Énergie RSA
McDougall	16.5	28	4.18	257.1	1	2002	RSP Hydro Inc
Magpie	20.5	70	12.95	225	3	2006	Hydromega GP, Inc
Chute Allard	17.83	66	10.57	200	6	2007	Hydro Quebec
Rapides-des-Coeurs	22.69	66	13.62	225	6	2007	Hydro Quebec
Vernon	10.97	50.97	5.08	144	4	2007	Transcanada Hydro NE, Inc
Hound Chute	9.87	53.6	4.71	163.6	2	2010	Ontario Power Generation
Lower Sturgeon	12.45	63.2	7.02	180	2	2010	Ontario Power Generation
Sandy Falls	9.05	66.7	5.27	180	1	2010	Ontario Power Generation
Chute Garneau	10.26	57.2	5.32	180	1	2010	Ville de Saguenay
Pont Arnaud	15.68	56.2	8	200	1	2010	Ville de Saguenay
Santa Rita	22.0	60.0	12.1	225	2	2013	Hidroeléctrica Santa Rita, SA
Upper White River	13.47	35.0	4.33	200	2	2013	Regional Power Inc
Lower White River	21.0	27.6	5.32	300	2	2013	Regional Power Inc

Tab.1: Litostroj Power's reference list of installed Saxo turbines

2. Detailed description of the Saxo turbine

Figure 1 shows typical cross sections of the Saxo turbine water passage with the inlet conduit, the elbow, the guide vane apparatus, the runner, the draft tube and the independently placed generator on top of the elbow. Numerous theoretical and numerical investigations of the Saxo turbine have been undertaken in design stage with the main focus on the design and validation of the selected hydraulic shape of the guide vanes and the runner blades, and the water passage region between them. A new runner blade row has been designed applying the improved streamline curvature method, Höfler et al. [2], considering the actual apparatus and actual shape of the guide vanes. Later on, the new runner blade row was analyzed, evaluated and validated using computational fluid dynamics (CFD) tools for viscous flow analysis, Gale, [3]. The considered water flow passage in CFD analyses started several meters before the inlet elbow (stable boundary condition) and ended with an extension after the draft tube exit; the whole turbine was considered at once. The analysis was performed for different guide vane openings and different runner blades positions; as a result, a 3D turbine efficiency charts were made. Finally, the hydraulic design and the CFD results have been successfully tested and validated by profound model testing (model runner diameter $D_M = 350$ mm), Djelić et al., [4].

Instead of a spiral casing as in Kaplan turbines, there is a compact elbow with deflector vanes, which predetermines and unifies the flow downstream to the stay vanes, guide vanes and the runner. Water is lead to the inlet elbow through a horizontal (i.e. 90°elbow) or an inclined penstock (> 90°elbow) where the slope of the penstock depends on available net head, turbine layout and terrain configuration. The inlet elbow is rather uncommon in comparison to standard turbine configurations; however, the compact elbow with deflector vanes has been intensely numerically and experimentally investigated and hydraulically optimized. With the correct configuration of the deflector vanes, the elbow produces a very small amount of local losses, Idelchik [5], and yields a uniform flow field downstream the elbow.

The vertical shaft alignment for the torque transmission from the runner to the generator is fed throughout the elbow. The sealing of the shaft at the top of the turbine elbow is quite simple, while the sealing is not necessary at the waterside. The system of lubricating-sealing water was carefully considered in order to assure appropriate filtering, water pressure and discharge at all operational conditions. The closed loop system of lubricating-sealing water was selected to prevent inflow of the unclean water from the turbine water passage also when the turbine is not in operation.

Stay vanes and conical guide vanes (distributor) are located downstream from the intake elbow. The guide vanes are used to adjust discharge and to enable best-efficiency operation (on-cam) by directing water to the runner blades. The guide vanes act as a swirl generator whose advantage is that it generates slightly forced vortex flow, due to which the velocity field ahead of the runner blades becomes more uniform, Nechleba, [6]. However, the guide vanes also partially obstruct the flow, especially at partial openings. The runner can be assembled with four, five or six regulated blades. Below the runner, there is a relatively short conical diffuser (less civil construction work) with an elbow and the square-sectioned draft tube outlet.

The design of the Saxo turbine is very rigid and the turbine shaft is vertical, which enables very good rotational dynamic characteristics during operation. The generator, which also serves as a flywheel, can be attached directly to the inlet elbow for smaller units, while for larger units the generator is normally attached to the concrete block surrounding the inlet elbow. The generator can be driven directly by the turbine shaft or with the aid of a rotation speed gearbox. The bottom bearing of the generator is at the same time the second guide bearing of the turbine, while the thrust (axial) bearing of the generator also takes the hydraulic axial loading from the runner.

One very important advantage of the Saxo turbine design, from the ecological point of view, is application of the water-lubricated and water-cooled turbine guide bearing near the turbine runner. The material of the bearing liner is molded polymer PTFE (commercial name: Teflon) with additives or sintered metal based on bronze. The choice of such bearing avoids use of oil or grease, and it simplifies maintenance to a great extent. The use of water-lubricated guide bearing significantly reduces chances for the contamination of the river water with oil or grease. The concept of the Saxo turbine is also fish friendly, which means that the water passage was designed to protect fish population in front of the pressure shocks and strikes by the runner in comparison to other comparable turbines (relatively lower rotational speed, lower number of runner blades, short high pressure section of the penstock, etc.).

The hydraulic power unit (HPU) for oil supply for the runner and distributor regultating mechanisms was minimized by increasing the hydraulic pressure up to 150 bars, and installation of a hydraulic piston pump (see Fig. 3). In addition to the compact HPU, the auxiliary systems of the Saxo turbine are limited to the system for the preparation of water for cooling, guide bearing lubrication and shaft sealing and a relatively simple water drainage system. The system for water preparation can serve also for cooling of the generator bearings if necessary. The generator requires a lubricating system for oil bearing. Auxiliary systems can be located close near the turbine itself.

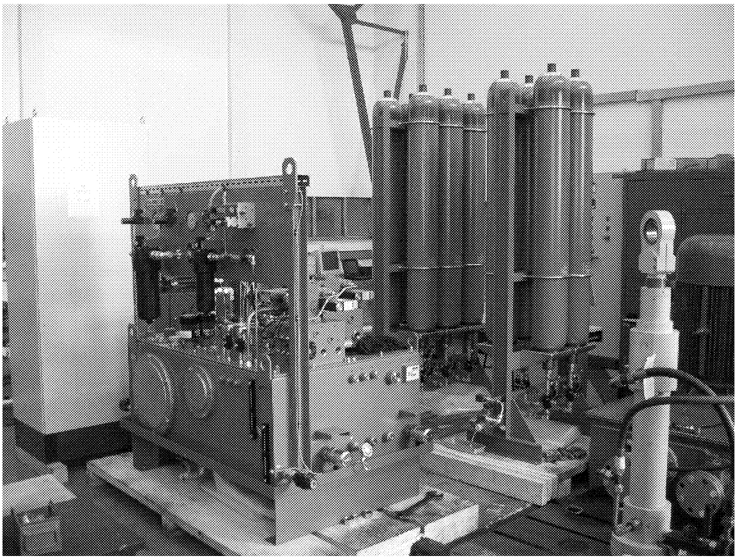

Fig.3: Typical Hydraulic power unit (HPU) for the Saxo turbine at workshop performance tests

The oil distributor is a hydraulic system device that is necessary for setting the appropriate on-cam angle of the runner blades. In the oil distributor, the oil flows under high pressure from the static tubes to the rotating tubes, which are installed inside the hollow generator and turbine shaft. The oil distributor for the Saxo turbine is installed at the top of the generator at the free end of the shaft. This is the best position with regards to inspection, control and maintenance.

3. Economical comparison

A simple comparison of economical parameters for a hypothetical reference HPP of total turbine power output of 40 MW is depicted below. The main design parameters are:

- rated net head: $H_{\mathrm{n,r}} = 20.5\,\mathrm{m}$
- rated total discharge: $Q_{\mathrm{r}} = 210\,\mathrm{m}^3/\mathrm{s}$

Conventional solution for these design parameters would be an arrangement of two Kaplan turbines; however based on overall economical evaluation, the best selection would be an arrangement of three Saxo turbines. Table 2 shows comparison of key economical parameters.

The Saxo units are typically smaller, therefore more Saxo units have to be incorporated into the power station. At first look, there are three Saxo units compared to two Kaplan units which by the bottom line yield higher investment for the mechanical equipment ($\sim 7\,\%$ more for turbines and generators). However, since the Saxo units are smaller (runner diameter 3100 mm) comparing to the Kaplan turbines (runner diameter 3800 mm) it is clear

Turbine Type / Parameter	Saxo turbine	Kaplan turbine	Units
Number of Turbines	3	2	
Runner Diameter	3100	3800	mm
Turbine With Auxiliaries	63	58	EUR/kW [%]
Electrical Equipment	4	3	EUR/kW [%]
Generator and Excitation	40	39	EUR/kW [%]
Total Unit Equipment	107	100	EUR/kW [%]
Power House Concrete	C	$1.8\,C$	m^3
Powerhouse Length (total)	L	$1.2\,L$	m
Powerhouse Height (total)	H	$1.05\,H$	m
Powerhouse Width (total)	W	$1.3\,W$	m
Turbine Installation Time/Unit	6	10	months
Turbine Production Time/Unit	20	20	months

Tab.2: Comparison of key economical parameters for reference 40 MW HPP

that height and length of the power house can be smaller for the arrangement of Saxo turbines (less concreting, less digging). Significant savings regarding the civil works are also accomplished due to the absence of the spiral case at the Saxo turbine and smaller draft tube. Figure 4 shows that arrangement of Kaplan units is wider mainly because of the semi-spiral case. The Saxo units are smaller, more compact and they can be placed closer to each other. Altogether it is estimated, there is 80 % more concreting needed during powerhouse construction for two Kaplan turbines compared to arrangement of three Saxo turbines.

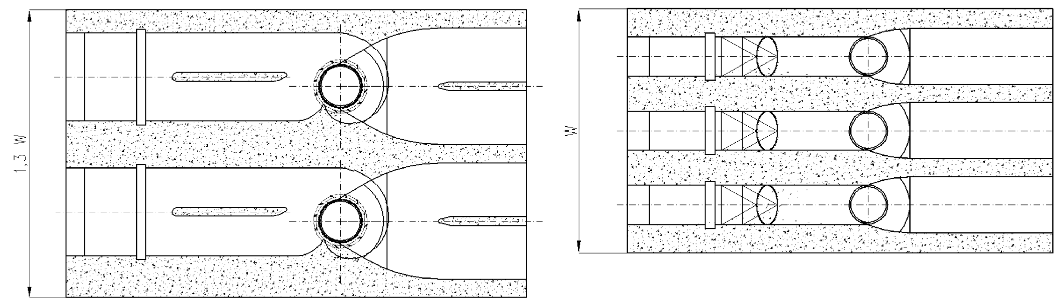

Fig.4: Comparison of reference powerhouse top views (left : arrangements of two Kaplan turbines, right : arrangement of three Saxo turbines)

The Saxo units have fewer problems with the handling, installation and erection of the equipment due to smaller components, which allows utilization of smaller powerhouse crane and consequently less bulky powerhouse structure and quicker installation of the factory pre-assembled components. The draft tube elbow can be made of concrete or steel. In the latter case, the draft tube elbow is placed on-site with a mobile crane, centered and concreted. Afterwards, the powerhouse is finished and the powerhouse crane is put into operation. The single-part inlet elbow is placed by the powerhouse crane, centered, anchored, and concreted. The preassembled stay ring and distributor assembly are lifted to the inlet elbow from the bottom floor. The erection of the turbine shaft is similar to that of a Kaplan turbine, but the runner is attached to the shaft with the aid of a shear ring rather than a classical flange. The runner is also lifted to the shaft from the floor bottom. The erection of the runner casing and the dismantling flange follows. At the same time, the generator and other equipment can be erected. Experiences show that the time needed for erection of one Saxo unit is up to 40 % shorter (6 months) than the time needed for erection of one Kaplan unit (10 months).

Arrangement of three units instead of two, yields additional operational flexibility. Smaller units can operate and utilize smaller discharges; combination of three units enables operation close to turbine best efficiency point for most of the operational time (bigger output with the same water potential, less interruptions during maintenance), better availability for electricity production, and in case of maintenance of one unit, there are still two units available for production.

4. Field feedback and experiences

During commissioning of Saxo units numerous tests have been conducted. One of the most interesting and exceptional tests is the runaway test which was for example required by Hydro Quebec. One unit out of twelve was randomly selected by the customer and the turbine was at full runaway speed for more than 10 minutes. The Chute Allard HPP unit withstands the test without the damage and only negligible maintenance work was required after the test.

Turbine performance, cavitation and energetic characteristics have been verified by extensive model testing already at the design phase, Djelić et al., [4]. During the commissioning an extensive index tests were performed on each installed unit as a relative efficiency measurement method, Čepa et al. [7]. The main purpose of the on-site index tests is to perform the final fine tuning of the unit wicket gate / runner blade operation cam relationships; however, a side result is also validation of the guaranteed efficiency. Very high and flat efficiency curve of the Saxo turbine is always a subject of doubt especially due to very good efficiency performance at part load. The energetic performance has been also verified numerously with Field Acceptance Tests based on current meters. Current meters based efficiency testing was performed on fourteen of the installed Saxo units, and for all of them favorable results were obtained. Good correlation between expected prototype efficiency, measured efficiency by index tests and measured efficiency by current meter method has been confirmed at all commissioned Saxo units.

Because the Saxo unit doesn't have the spiral case, the Winter Kennedy (WK) measuring taps are installed at the front and the side of the stay vanes. The discharge measurement based on such WK disposition turned out to be a reliable and accurate method.

Due to the water lubricated Teflon turbine bearing and corresponding clearances, which is braced by relatively long bearing cone, small radial forces on the turbine runner can induce relatively large radial shaft displacement. Therefore, the turbine runner must be well mechanically and hydraulically balanced. There was a case on one of the Rapides-des-Coeurs HPP units, where the turbine runner was on-site mechanically balanced to correct the hydraulic unbalance. It was found out that unbalance force of 2500 N caused shaft displacement close to $300\,\mu$m. The magnitude of unbalanced force is small comparing to the maximal design load and as such is far from being harmful for the bearing. After fine-balancing the unit runs smoothly within the acceptable limits. To avoid further on-site balancing, additional precautions were introduced in the workshop and stringent tolerances on the runner blades installation angle were introduced to minimize the hydraulic unbalance of the runner.

At part load where runner is still fully closed and the turbine operates off-cam, a slight vortex can be noticed below the runner. That phenomena influence the runner, forcing it in low frequency procession around the borders of the bearing (see Figure 5). The forces are low and not harmful for the bearing, which was proved by several years of successful bearing performance on Saxo units. The only issue with shaft displacement procession in part load operation is how the vibration protection system can be adjusted. Problem is solved in such way that only the 1st harmonic of the shaft run-out is plotted and analyzed by the protection system.

Axial force itself has been measured and controlled on several units, however on most Saxo units, maximal off-cam upward axial forces are slightly smaller than the weight of the rotating masses. Weight of the rotating masses is low comparing to the classical Kaplan units. At extreme off-cam operation conditions the upward axial thrust can be higher as the weight of the rotating masses. Such condition may occur at load rejection or emergency shutdown. For integrated protection an 'Upward stop ring' on all Saxo units is installed, which is designed to withstand upward forces for the time of two minutes.

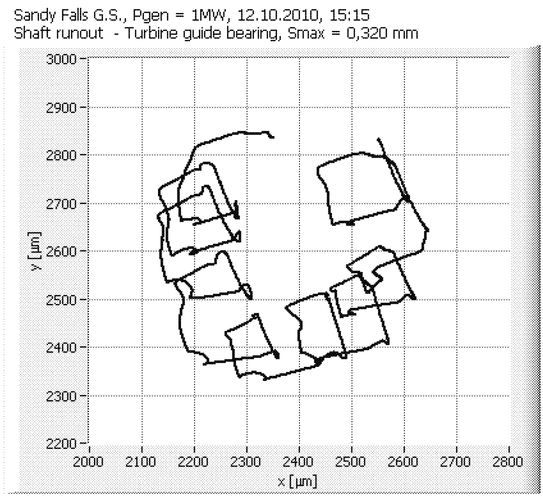

Fig.5: Shaft runout at Sandy Falls HPP at part load ($P_{\text{gen}} = 1\,MW$)

5. Conclusions

Analysis of the design and hydraulic characteristics of the Saxo turbine and its comparison to Kaplan and tubular turbines clearly shows advantages of the Saxo turbine over a wide range of operating conditions. The vertical axial tubular unit in S-configuration has been developed as a low-cost turbine. Its configuration ensures high performance and reliability, easy erection, minimized civil construction works, easy maintenance and long operation lifetime. The Saxo turbine has been optimized, standardized, and adopted for small and medium hydro power plants for net heads up to 30 meters, flows up to $85\,\text{m}^3/\text{s}$, and rated output up to 20 MW. The Saxo turbine is suitable for new projects as well as for refurbishment of Kaplan unit power plants or low-head Francis unit power plants. The cost-effective Saxo units are a good choice for environmentally friendly operation offering the quickest return of the investment.

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